NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

LOGISTICS SUPPLY OF THE DISTRIBUTED AIR WING

by

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September 2014

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704–0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	09-26-2014	Master's Thesis 09-26-2013 to 09-26-2014

4. TITLE AND SUBTITLE

LOGISTICS SUPPLY OF THE DISTRIBUTED AIR WING

5. FUNDING NUMBERS

6. AUTHOR(S)

Chee Siong Ong

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Postgraduate School
Monterey, CA 93943

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views expressed in this document are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol Number: N/A.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

This thesis was performed at the MOVES Institute

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

The use of the aircraft carrier has been the norm for delivering sizable amounts of air power swiftly to any part of the world. A capstone project, conducted by the system engineering curriculum, proposed to distribute the air assets from the aircraft carrier to multiple Expeditionary Airbases (EABs), which are land bases located within the operating theater. This thesis studies the logistical demands of the EABs, and adopts the Marine Aviation Logistics Support Program II (MALSP II) concept for the logistics supply of the Distributed Air Wing. Airship, fixed wing Unmanned Air Vehicle (UAV), and rotary wing UAV are explored as the main cargo transportation means.

This thesis develops a vehicle routing optimization model to optimize the transportation fleet size and mix, and a discrete event simulation to analyze the logistics concept. Experiments are conducted to determine the feasibility and cost-effectiveness of using cargo UAVs, using cargo trucks as a reference for comparisons. All platforms achieved the three days' turnaround time, as stipulated by MALSP II. The airship is found to be the most cost-effective solution. Rotary wing and fixed wing UAVs deliver their supplies much faster, but are more suitable for quick response missions, instead of large cargo deliveries.

14. SUBJECT TERMS

distributed air wing, logistics, supply, unmanned air systems, cargo UAS, unmanned systems, discrete event simulation, vehicle routing problem, optimization.

15. NUMBER OF PAGES 123

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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LOGISTICS SUPPLY OF THE DISTRIBUTED AIR WING

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MODELING, VIRTUAL ENVIRONMENTS, AND SIMULATION

from the

NAVAL POSTGRADUATE SCHOOL
September 2014

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List of Acronyms and Abbreviations

A2AD Anti-Access Anti-Denial
ACE Aviation Combat Element
ARES Aerial Re-configurable Embedded Systems
CVW Carrier Air Wing
DARPA Defense Advanced Research Projects Agency
DAW Distributed Air Wing
DES Discrete Event Simulation
DoD Department of Defense
EAB Expeditionary Airbase
ESB Expeditionary Supply Base
FISP Fly-in Support Packages
FW Fixed Wing
FOB Forward Operating Base
LRU Line Replaceable Units
MALSP Marine Aviation Logistic Support Program
MIP Mixed Integer Programming
MRE Meal, Ready to Eat
MOB Main Operating Base
NPS Naval Postgraduate School
OPNAV N9I Navy Operations Warfare Integration
PMALS Parent Marine Aviation Logistics Support
RW Rotary Wing
SEA-20B System Engineering and Analysis Cohort 20B
STOVL Short Take Off Vertical Landing
UAS Unmanned Air Systems
UAV Unmanned Air Vehicles
USG United States Government
UGR Utilized Group Ration
VRP Vehicle Routing Problem
VTOL Vertical Take Off Landing

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Acknowledgments

I would like to thank Dr. Timothy Chung, from the Systems Engineering Department, for his guidance in my thesis. I would also like to thank Major Seagren, from the Operations Research Department, for his advice on the Marine Aviation Logistics Supply Program. Finally, I am very grateful to my company, Defence Science and Technology Agency, for sponsoring my studies in the Naval Postgraduate School, and giving me the opportunity to explore this thesis topic.

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CHAPTER 1: Introduction

1.1 Overview of the Distributed Air Wing

Concentrated forces have been the norm of the United States (U.S.) Navy to supply forward forces for war or peacekeeping. The use of concentrated forces revolved around the use of the aircraft carrier to deliver sizable amount of air power swiftly to any part of the world. The Carrier Air Wing (CVW) is the air component of the aircraft carrier and has been the mainstay of the U.S. Navy. The CVW provides maneuverable air power to project a forward presence, provide sea control and deep strike capabilities to deter adversaries [1]. Apart from the defense roles, the CVW is also prominent in supporting humanitarian missions around the world.

Over the years, spiraling developmental and maintenance costs have challenged the sustainability of aircraft carriers. Secondly, such large forces are vulnerable to attacks from adversaries, as they are more easily detected, and rely heavily upon defensive convoys to protect them. Finally, with the emergence of geographically dispersed adversaries around the world, the concept of using aircraft carrier fleets could be overwhelmed when handling diverse missions simultaneously. As a result, defense analysts harbor doubts on the capability of aircraft carriers to handle the mobility and effectiveness of future warfare [2], [3].

To address such issues, the System Engineering and Analysis Cohort 20B (SEA-20B) analyzed the risks of using a CVW and recommended three solutions to mitigate the risks. The focus of the SEA-20B project was to reduce the risks and costs of operations, while maintaining or exceeding the current CVW capabilities.

1.2 Background of the SEA-20B Project

The SEA-20B project was conducted by the System Engineering Analysis Curriculum as a capstone project for students to apply lessons learned during the curriculum to resolve real-world problems. Seventeen students from the United States, Singapore, Israel, and

Taiwan participated.

The team was tasked by its project sponsor, Navy Operations Warfare Integration (OPNAV N9I), with the following problem statement:

> Design a system of systems and the concept of operations to employ naval air assets in a range of missions to augment naval operations or to conduct specified tasking in the 2025-2030 timeframe and beyond. Consider manned and unmanned air systems (UAS) to execute direct support to the naval missions across the kill chain spectrum within a distributed air wing concept.

SEA-20B analyzed the current threats, situations, and vulnerabilities of the CVW and determined that the aircraft carrier possesses high risks of operations. With technological advances, adversaries could deploy long-range missiles, UAS or advanced aircraft technologies to effectively destroy or damage the aircraft carrier [3], [4]. This loss could significantly impact the functionality of the air wing support of forward troops, since a damaged carrier would mean the loss of a sea base to launch the aircraft for operations. In addition, there are inherent risks of losing a notional asset which could affect the psychology and morale of the troops [2]–[4].

1.3 Proposed Solutions of SEA-20B

To overcome the risks, SEA-20B defined an effective need to improve on the current CVW capabilities. The proposed solution is to introduce a new naval air force structure and define new concepts of operation, which integrate UAS with manned air, surface, and subsurface systems in a way that maintains or exceeds current mission effectiveness while reducing both cost and risk involved with operating under an Anti-Access Anti-Denial (A2AD) umbrella [5]. To address the problems, SEA-20B proposes two Distributed Air Wing (DAW) concepts to mitigate the risks.

The first solution is to distribute the responsibility of the aircraft carrier to other Naval platforms, by using a combination of manned and unmanned aircraft for operations. First, Sea-Scouts will provide the full spectrum of sensor capabilities to the operating theater. Each Sea Scout comprises of Unmanned Air Vehicles (UAVs) and a small UAV carrier.

The UAVs will detect surface and air threats, and have the capabilities to relay communications to the forward troops. These capabilities will be realized by utilizing , for example, the Boeing A160 Hummingbird UAV. In order to provide the distributed capabilities, the UAVs will be carried by small surface carriers, currently developed by Naval Air Warfare Center (China Lake), to launch and manage UAV operations. Additionally, the UAVs carrying air-to-air missiles will operate alongside manned fighter aircraft to protect them from air threats in a manned-unmanned teaming construct [5].

The second solution is to disperse the aircraft from the CVW to several land airbases, also known as Expeditionary Air Bases (EAB), with the focus of spreading the risks of fatality from a single point (i.e., the aircraft carrier, to the several land bases). Dummy land airbases are inserted to complicate the adversary's capabilities to detect the actual airbase. These airbases are designed to be set up within three days, utilizing highways as short runways for the Short Take Off Vertical Landing (STOVL) aircraft F-35B, and/or civilian airfields with reinforced defense capabilities. The bases would host a full Air Combat Element (ACE) of aircraft, typically six aircraft, to provide strike capabilities to the operations, see Figure 1.1. This figure shows the distribution of the Expeditionary Airbases (EABs) to locations in Vietnam and Philippines, in an Anti-Access Area Denial (A2AD) scenario in the South China Sea. The figure also shows the locations of the Guided Missile Destroyers (DDGs) patrolling around the Spratly Islands.

Figure 1.1: Locations of the Expeditionary Air Bases

1.4 Thesis Problem Overview

In terms of logistics, the aircraft carrier serves as a single point of contact to store and supply logistics. The aircraft carrier would typically store sufficient supplies, such as water, food, repair parts, and fuel, to sustain the air wing operations for months. Logistical demands of the CVW are consolidated by the aircraft carrier and sent together with other requests to the main logistics bases in the U.S. The supplies are usually delivered by the sealift command to the aircraft carrier. The carrier stores the supplies in its warehouse and distributes them to the air wing when required. In other words, these arrangements act in a one-to-one supply-demand concept (one sealift supply to one aircraft carrier).

With the proposed DAW concept, the air wing is dispersed into different EABs. The size of forces in each location is smaller, meaning that the logistical demand of each base is smaller. The logistics command will now have to deploy multiple units to deliver the supplies to each EAB. This arrangement acts like a one-to-many supply-demand concept

(one supply depot to many EABs). The demands on the logistical units invariably increase since they have to travel farther, faster, and to more locations to fulfill the demands of the air wing.

Some questions from the one-to-many supply-demand concept are as follows:

1. What are the platforms and force composition required to support the logistical supply of the DAW?
2. Where should the logistics center, where the warehouses, airfields and cargo transports are located, be located in order to effectively reach the EABs and support the demands of each EAB?
3. How much supplies should each EAB store to sustain its operations?
4. Could a cargo UAV be used to resupply the DAW?

1.5 Objectives of the Thesis

This thesis explores the logistics problems of the DAW and provides solutions for resupplying the EABs. In addition, this thesis explores the use of cargo UAV to deliver logistical supplies to the EABs. To support the recommendations, the transportation fleet size and the types of transports used to support the delivery of cargo were explored in this thesis. A discrete event simulation was developed to run to test the concept to determine if the recommendations are sound.

1.6 Scope of the Thesis

This thesis first identified a suitable logistic concept to use in the DAW operation. This includes identifying suitable bases, acting as main supply bases for the EABs, and transportation platforms to support the logistics operations.

After identifying the bases and platforms, this thesis uses a two-stage approach to simulate the logistics flow and determine the feasibility of the recommended platforms.

Stage one uses a form of the optimization model to determine the force structure of the Naval units supporting the logistics resupply. Using the Vehicle Routing Problem (VRP) optimization model, the optimal route of delivery can be derived. At the same time, the

VRP model recommends the platform types and fleet size required to support the logistical supplies.

Stage two uses a Discrete Event Simulation (DES) to simulate the logistical demands of the DAW. Using the data from the optimization model, the effects and feasibility of using the logistics concept were explored in the simulation model.

1.7 Organization of the Thesis

This report is organized into the following chapters to provide a structured flow of this thesis.

Chapter 1 – Introduction
This chapter provides the introduction, objectives, and scope of this thesis.

Chapter 2 – Logistics Concept
This chapter provides the logistics concepts adopted by this thesis. It includes the demands of EABs, the recommended transportation vehicles, and the supply bases to support proposed logistics concept.

Chapter 3 – Methodology
This chapter describes the general methodology used. The model descriptions, performance measures, and developmental approach are described here.

Chapter 4 – Vehicle Routing Problem Model Formulation
This chapter describes the equations used for the vehicle routing optimization model.

Chapter 5 – Discrete Event Simulation
This chapter describes the Discrete Event Simulation models developed in this thesis.

Chapter 6 – Simulation Results and Analysis
This chapter discusses the findings of the simulation, and provides the recommendations for the logistical supply of the DAW.

Chapter 7 – Conclusions
This chapter summarizes this thesis and discusses the future works applicable to this thesis.

CHAPTER 2: Logistical Concept

2.1 Scenario Formulation

Using an A2AD scenario in the South China Sea as the main context, a study was conducted by SEA-20B to determine the feasibility of the recommended solutions. The objective of the study was to prevent hostile threats from reaching the Spratly Islands. An optimization was performed by SEA-20B to determine the optimal base locations and the force composition needed to provide full protective coverage of the South China Sea. To achieve this objective, the EABs are set up in Vietnam and Philippines. Each EAB houses six F-35B aircraft and three MQ-8 Fire-Scouts to provide the full range of strike and firepower capabilities to prevent the adversaries from approaching the Spratly Islands. Figure 2.1 shows the proposed locations of the EABs in the distributed air wing.

The force structure of each EAB and the costs of the force are shown in Table 2.1

EAB (Expeditionary Airbase)	QTY	Unit Cost (USD)	Total Unit Cost (USD)
F-35B	6	200.2 M	1,201.5 M
MQ-8 Fire-Scout	2	18.3 M	36.6 M
AEW Assets (MH-60S or R)	2	36.9 M	73.9 M
EAB	1	100.0 M	100.0 M

Table 2.1: Cost and Force Structure of each EAB
(Reprinted from [5])

2.2 Logistics Concept

The logistical demands of the EAB and the methods to resupply the EABs are relatively unknown now. In essence, the main aim of logistics supply is to reduce the costs associated with the storage of goods, while ensuring the goods are delivered on time, on target to the bases.

In 2010, the Marine Corps revamped the system of supplying logistics to the Forward Operating Bases (FOBs). The program, Marine Aviation Logistic Support Program (MALSP II),

Figure 2.1: Locations of the Proposed Expeditionary Air Bases for the Distributed Air Wing in SEA-20B

is the next generation aviation logistics designed to meet the changing requirements of the Aviation Combat Element. Instead of delivering the logistical supplies directly from the parent supply base to the FOBs, a series of intermediate nodes are strategically placed to form a supply chain linking the parent node to the FOBs [6]–[8]. To illustrate the transformation, Callan [6] defines the MALSP as a series of network from the U.S. to the FOBs. A Parent Marine Logistics Supply (Parent MALS) remains in the U.S. to coordinate the requests in the supply chain. A series of intermediate nodes, known as Expeditionary Supply Bases (ESBs) is set up to coordinate the logistics within a geographical region. The Main Operating Base (MOB), which is located near the FOBs, falls under the control of the ESB. Under these arrangements, the aim is to transform the operations to follow a Just-In-Time concept and reduce the reliance on the parent base. Figure 2.2 shows the transformation of the old MALSP concept into MALSP II.

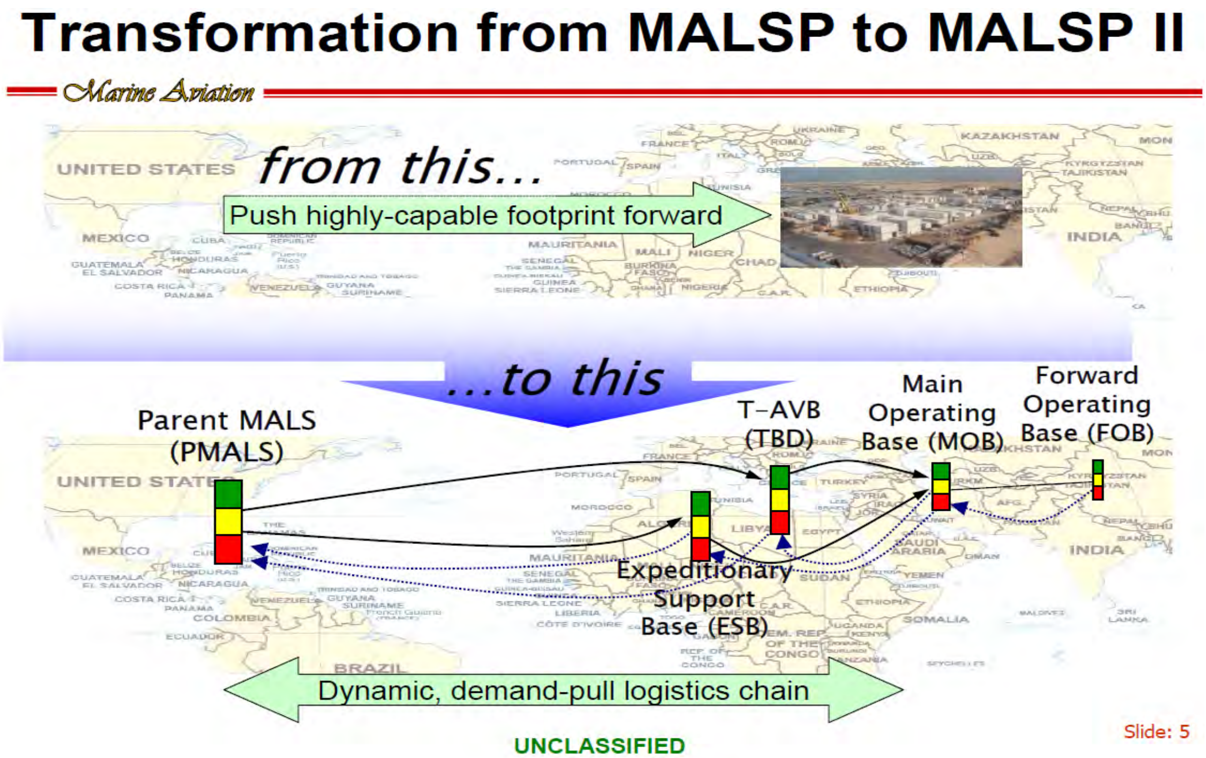

Figure 2.2: Marine Aviation Logistics Support Program II Concept. Reprinted from [6].

The idea of MALSP II is to use Just-In-Time and Push-Pull Methodologies for resupplying supplies. Just-In-Time methodology means the replenishment request is synchronized with the consumption rate. Each request is only activated after the supplies reach a certain level. Push-Pull methodology means the upper echelon requests supplies from its immediate upper echelon after the lower echelon has requested for supply. For example, the MOB requests for supplies from the ESB, only after the FOB had requested for supplies [6]–[8].

This is a move away from the traditional schedule-based method, whereby the PMALS estimates the demands of the FOBs and sends the supply on a regular basis. This method is inefficient as there could be a mismatch in the supply and demand quantities. Furthermore, since the deliveries are scheduled, it is inflexible in meeting irregular demands. For example, there may be increased use in the aircraft that are not scheduled to counter hostile threats or perform additional missions. As a result, the aircraft might require more supplies than usual, but only for those few days. These requests might not be accommodated if the supplies had left the depot and have to be delayed until the next shipment [6]–[8].

With the setup of the MALSP II supply chain, the supplies are held closer to the operating theater and are made more accessible to the FOB. Deliveries are expected to be more efficient due to the proximity of the MOB to the FOB. In addition, as with a Just-In-Time concept, the holding costs and warehouse costs are effectively reduced.

This thesis utilizes the concept of MALSP II for resupplying the EABs. In comparison, the EAB is similar in nature to the FOB. Both are operating within the operating theater and both require supplies from the PMALS. Both are small-scale bases dispersed in different locations within the theater and are equipped with essential supplies to last a short period (typically up to 30 days) of operations.

With the new supply chain, the FOB no longer requests their demands to the PMALS. Instead, the MOB is the main point of contact for the FOBs to request for supplies. As proposed by Callan [6], the MOB is expected to carry enough supplies to satisfy the demands of the FOB. The turnaround time, from the time the FOB request for supplies, to the time the FOB receives the requested supply, is expected to be three days. Figure 2.3 shows the expected time to replenish between the supply nodes. The three days turnaround time are used as a guideline to determine the locations of MOBs and force structure of the transportation fleet.

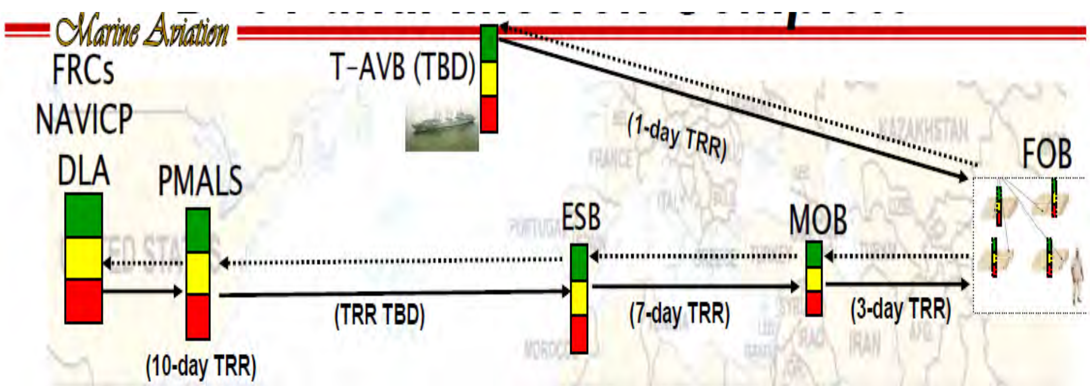

Figure 2.3: Time To Replenish Requirement (Note the day turnaround time between the MOB and FOB. Reprinted from [6].

2.3 Locations of the Logistics Center

The supply chain consists of intermediate nodes between the PMALS and the FOBs. Using South China Sea scenario to explore the concept, this thesis recommends using the Sembawang Airbase in Singapore and the Rota Naval Base to link the PMALS in the U.S. to Vietnam, using the North Atlantic Route. The Cam Ranh Bay Vietnam is selected as the site for the MOB to command and control the supplies within Vietnam and connect to the PMALS via Sembawang Airbase.

Guam Naval Base is recommended to link Philippines to the PMALS via the Pacific Route. The Subic Bay in Philippines is selected as the site to command and control the supplies within Vietnam and connect to the PMALS via Guam Naval Base. The following subsections provide the rationale behind the selections.

2.3.1 Expeditionary Supply Bases

Guam Naval Base

The Guam Naval Base formerly housed the U.S. Navy commands supporting the Pacific Fleet [9]. Logistics commands, such as sealift units, are available to provide support to the pacific fleet. However, Guam is considerably farther from Philippines and it takes about 10 hours round-trip to airlift supplies or up to several days to sea lift supplies to the EABs. Hence, it is not considered as a choice for the MOB. However, being in the middle of the Pacific Ocean and serving the western part of the Pacific Ocean, the Guam Naval Base would be a good intermediate point between the San Diego Naval Base and the Philippines.

Sembawang Naval Base, Singapore

The Sembawang Naval Base is a deep-water base serving as a logistics agent for resupplying food, ordnances, fuel , and repair parts for the Pacific Fleet. It is considerably further away from Vietnam, when compared to the Cam Ranh Base, and would take about double the time to transport supplies to the EAB. However, the Sembawang Naval Base could provide a good alternative for Cam Ranh Base as a MOB.

The proximity to both Europe and Asia provides a good bridge for the North Atlantic logistics centers to link up with the Pacific fleets. One suggestion is to set up two ESBs, one in Europe and one in Singapore, to link the U.S. to the South China Sea via the Atlantic

route. The supply chain would be longer, but with the support and protection from strong allies in Europe and the accessibility of sea-lanes from the Suez Canal to the Malacca Straits, setting up two ESBs to link Europe to the U.S. provides a reliable source of supply.

Rota Naval Base, Spain

The Rota Naval Base is located halfway between the U.S. and southwest Asia. Its main interest is to support the U.S. platforms by resupplying cargo, fuel, and ordnances to the units within the region between the U.S. and southwest Asia. [10]. The Naval Base spans an area of about 6,000 acres. It also plays a major role in the support of the U.S. Navy and NATO forces serving the region.

Figure 2.4 shows the proposed intermediate ESBs connecting the U.S. to the South China Sea.

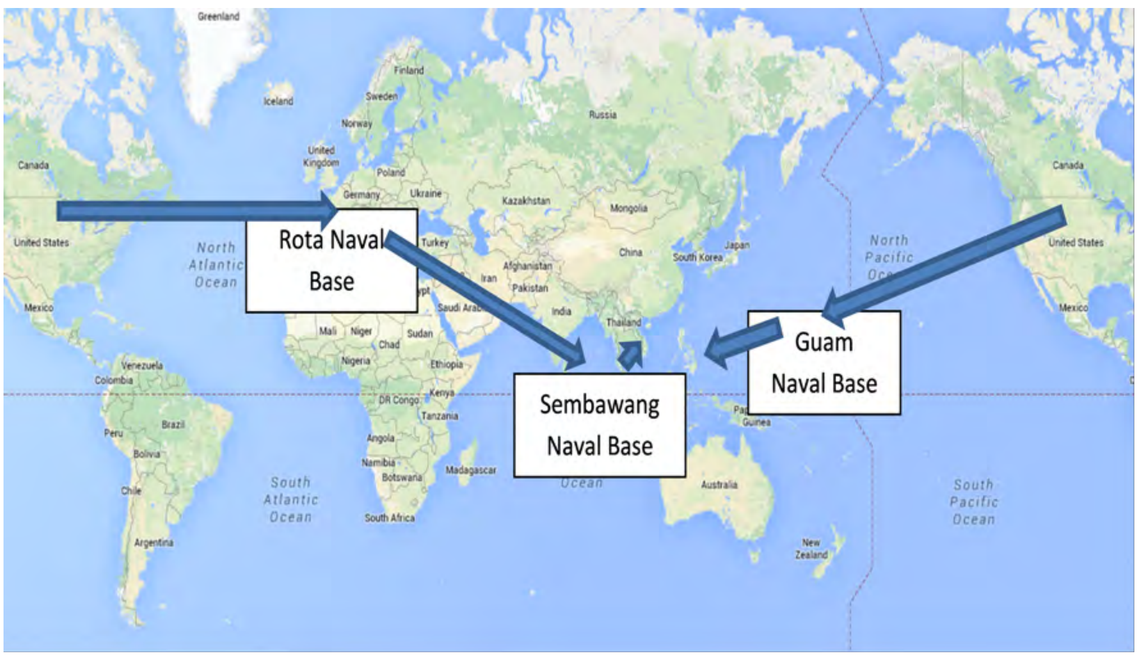

Figure 2.4: Proposed Locations of the Expeditionary Supply Bases

2.3.2 Main Operating Base

Subic Bay, Philippines

The Subic Bay in Luzon, Philippines, was formerly home to a U.S. naval base equipped with ship repairs and logistical facilities, which supported the Pacific fleets during the Vietnam War. However, a military agreement established in 1947, between the U.S. and the Philippines, expired in 1991 despite requests from the U.S. government to extend the agreement. Following better ties with the U.S., Philippines expressed their openness to welcome the U.S. Navy to establish a base in the Subic Bay. Philippine Defense Secretary, Voltaire Gazmin, announced that a proposal was raised during the Two Plus Two Ministerial Consultations in Washington, D.C., in April 2012, for the U.S. to access the facilities within the Bay [11], [12].

Advantages of using the Subic Bay as a MOB are as follows:

1. The Subic Bay provides deep-water facilities and it was already once used by the U.S. Navy. The U.S. Navy has deep knowledge on the cultural aspects and the geographical area around the Subic Bay. With the blessings of the Philippines, the U.S. Navy could adapt easily to the environment without any political barriers.
2. The EABs are located in both Luzon and Palawan. The proximity of the Subic Bay to both areas would provide easier accessibility to the air platforms requiring repairs and logistical supplies.
3. Subic Bay International Airport is situated in the Subic Bay. The U.S. Navy could leverage the airport as an airbase to provide airlift capabilities for transportation of logistical supplies to the EABs.
4. Proximity to the Guam Naval Base, which could act as the intermediate point between San Diego and Subic Bay, would ensure the supplies would reach the Subic Bay area within the stipulated MALSP delivery period.

Cam Ranh Bay, Vietnam

Cam Ranh Bay formerly housed a naval base to support the 7th Fleet during the Vietnam War. Following the withdrawal of the U.S. forces from Vietnam, the U.S. Navy vacated the area. After the withdrawal, it was used by South Vietnamese forces and the Russian Navy until 1993. The site has since been converted for civilian use [13].

With the escalating tense relationship with China, Vietnam built up the Cam Ranh Bay and welcomed foreign navies to use the facilities in an attempt to project their force and to counter the threats from China. Vietnam hired Russian consultants to construct new ship-repairs facilities, which will be ready by 2015, and divided the Bay into three zones. They are namely the Military, Logistics, and Technical Service Zone. [13].

The Vietnam Navy welcomed all foreign navies, including those of Russia and the United States, to access the Cam Ranh Bay. In 2012, the U.S. Secretary of Defense, Leon Panetta, visited the Cam Ranh Bay and expressed interests in expanding their presence there for maritime, search and rescue, and disaster relief operations. Several military experts indicated that this could be a sign of the U.S. Navy returning to the Bay [14], [15].

Advantages of using the Cam Ranh Bay as a MOB are as follows:

1. The Cam Ranh Bay is a deep-water base used frequently by the U.S. Marines merchant supply ships for repair services. The base was upgraded with logistical facilities, which could be used by the U.S. Naval forces. Therefore, substantial amounts of time could be saved from building its own facilities.
2. The EABs are located in Central and North Vietnam. The proximity of the Cam Ranh Bay to the bases could effectively reduce the delivery time for resupplying the EABs.
3. Cam Ranh International Airport is located in the Bay. The proximity to the airport would provide smooth access to transit the goods from the warehouse to the transport aircraft.
4. The Sembawang Naval Base, Singapore, currently acts as a logistics agent for U.S. Pacific Fleet. The proximity to the Sembawang Base, which could act as the intermediate node between the U.S. and Vietnam, could enhance the efficiency to send supplies to Vietnam.

Figure 2.5 shows the proposed locations of the MOBs to support the EABs in Vietnam and Philippines. The red circle denotes the coverage of each MOBs.

Figure 2.5: Proposed Locations of the Main Operation Bases

2.4 Cargo UAVs for Delivering the Supplies

In 2013, the U.S. Congress passed legislation for the Federation Aviation Authorities (FAA) to open the skies by September 2015 for the UAVs to operate within the U.S. [16]. Following suit, several private companies, such Amazon and FedEx, announced plans to use UAVs to deliver cargo to their customers by 2018. In July 2014, Amazon requested the FAA to tests their UAV, with the aim of meeting their goal of delivering packages to their customers within an hour [17]. This shift could signify the start of cargo UAV moving into the skies of the U.S. and challenge traditional means of cargo transportation, such as trucks and ships.

The rise of the UAV coincides with the advancement of technology. Over the past several years, sensing, communication, navigational, and automation systems began to diminish

and stabilize, to a point that UAVs could fly automatically and perform missions without guidance from a pilot. However, UAV technologies are still at too early a stage to be considered for mainstream activities. Nonetheless, many analysts expect that to change by 2025. They predict that with the improvements in sensor and automation technologies, UAVs could eventually provide mainstream activities and possibly replace cargo trucks and ships by 2025 [18].

The concept of using cargo UAVs is not new to the U.S. military. In 2012, two unmanned helicopters, known as KMAX, were sent to Afghanistan as a trial of concept for the UAVs to deliver logistics supplies to the forward troops. By 2014, the KMAX helicopters flew nearly 300,000 hours and proved themselves a cheap and efficient way of delivering goods from point to point. Operational availability was 90%, with 5% downtime due to inclement weather and the other 5% downtime due to maintenance and servicing. Flight cost per hour was as low as $1200 [19]. In addition, feedback from the Marines suggests that KMAX is more responsive than manned vehicles, such as C-130 and convoy trucks.

In 2010, ONR discussed the requirements of cargo UAV with industry to propose long-term measures for developing cargo UAVs [20]. In November 2011, the DOD [21] reported to the Congress that a cargo UAV working group was formed to address and look into the needs of cargo UAV to support the logistical requirements. By 2013, initiatives were undertaken by DARPA [22], [23], defense industry [24], and the DOD to build experimental Vertical Take Off Landing (VTOL) UAVs to support the logistics resupply. The initiatives by the U.S. government and industry show that serious efforts are being invested to make cargo UAVs a reality. The consensus by the experimental programs is to develop a proof of concept by 2016-to-2018 and, if successful, develop cargo UAV for operations by 2025.

Thus, there is a high possibility that cargo UAV could eventually replace convoy trucks as the main means to transport cargo. To address that, this thesis embraces these technologies to transport cargo between the MOB and FOB.

2.4.1 Reasons for Using Cargo UAV

Efficiency

Manned cargo air vehicles, such as C17 and C130 fixed wing aircraft, require long runways, about 7,600 ft. long, for take-off and landing. The EABs are constructed out of highways, small airfields and dirt roads and the runways are expected to be short (up to 500 ft.). One of the reasons why SEA-20B proposes the F-35B as the choice of attack aircraft is the ability for it to take off from short runways as short as 450 ft. [5]. With STOVL UAV capabilities, the aircraft would not place too much demand on the requirements of a runway.

UAV technologies are increasingly improving [25]. VTOL cargo UAVs are extensively experimented by DOD and DARPA. The extensive research and the opening up of opportunities for commercial cargo UAV bodes well for the cargo UAV development, which will eventually lead to expediting efforts for the improvement of UAV.

UAVs could perform their job autonomously for long hours and fly to its destination accurately, with or without the pilot operating it. In the *Unmanned Air System Integrated Roadmap* outlined by the DOD [26], the aim of the future UAV operations is to have one pilot manage up to six aircraft concurrently. This could effectively reduce manpower needs in comparison to traditional aircraft operations.

UAVs are an efficient concept for delivering small quantities of supplies. For example, the food, parts, and water supplies could be requested in small quantities but they would not fill up a C130. It would be a waste of the cargo space to fulfill such small orders [27].

Risks

Fatigue and pilot errors are generally the common causes of accidents in the aviation industry. Pilots have to fly long hours to and from the EABs to deliver supplies. The job is considered boring, tiring, and tedious and places many demands on the pilots. UAV could change this by lifting the responsibilities from the pilots. UAV could fly in total darkness, perform a job for long hours without rest, and fly into dangerous territory without risks to any human lives [18].

Rugged terrain, ambushes, and Improvised Explosive Devices (IEDs) along the routes have made ground transports dangerous and risky. According to DARPA [28], a UAV helps to

circumvent problems associated with ground transports by avoiding the dangers associated with IEDs and hostile ground troops, and navigation of the rugged terrains.

Cost-Effectiveness

A survey conducted by the American Security Project [29] has shown that UAVs are more cost-effective than manned aircraft. For example, KMAX takes about two man-hours to prepare and fix before flights. Flight cost per hour is about $1,200 per hour, compared to $11,000 per hour for the Chinook CH-53E heavy-lift helicopter.

2.4.2 Categories of Cargo UAV

As mentioned in the previous sections, the U.S. Military are developing cargo UAV prototypes with the aim of using cargo UAV for mainstream cargo delivery by 2025. The broad categories of UAVs under development are classified into three main categories. They are: (1) Fixed Wing VTOL, (2) Rotary Wing VTOL and (3) Airships. The following sections provide details on the aircraft currently under development.

Fixed Wing VTOL Cargo UAV

Following the success of KMAX, DARPA is actively searching for faster aircraft that could deliver cargo faster, better and longer. To achieve that, the DARPA is embarking on fixed wing technologies, which could take-off, and land vertically. Two such programs are prominently declared and their contracts were awarded in 2013 to expedite the efforts to realize the vision.

According to DARPA, X-plane, an experimental VTOL plane, will have cross-pollination between fixed-wing and rotary-wing aircraft [22]. The plane seeks to overcome the ability to increase top speed without sacrificing range, efficiency, or ability to do useful work. In December 2013, prime contract is awarded to Aurora Flight Sciences.

The objectives stated in the list of requirements from DARPA [22] are:

1. Speed: Achieve a top sustained flight speed of 300-400 knots.
2. Hover Efficiency: Raise hover efficiency from 60 percent to at least 75 percent.
3. Cruise Efficiency: Present a more favorable cruise lift-to-drag ratio of at least 10, up from 5-6.

4. Useful Load Capacity: Maintain the ability to perform useful work by carrying a useful load of at least 40 percent of the vehicle, with projected gross weight of 10,000 to 12,000 pounds.

X-plane is scheduled for flight tests by 2018. If the experiment is successful, the aircraft is likely to be expanded to gross weight of up to 24,000 pounds with about 40 percent for payload – i.e., about 10,000 pounds of payload eventually [22]. Figure2.6 shows the X-Plane concept developed currently by DARPA.

Figure 2.6: X-Plane Concept (Reprinted from [22])

Another fixed-wing VTOL UAV in the pipeline is the Aerial Reconfigurable Embedded Systems (ARES). According to DARPA , many commands in the operating theater require dedicated helicopters for their missions but do not have one [28]. The transformers program would design a UAV that is controllable by units using applications installed on their mobile phones or tablets. The UAV could carry up to 3,000 pounds of cargo and it could be used for intelligence, surveillance, or cargo pickup and delivery purposes. The ability to cruise at high speed and touch down at landing zones half the size of manned helicopters would allow it to land at rugged terrains or on-board a landing transport ship. Lockheed Martin's Skunk Works, in collaboration with Piasecki Aircraft, is developing the aircraft. The program is currently in its final phase and is scheduled for flight tests by 2016.

Rotary Wing VTOL Cargo UAV

This category also possesses proven statistics, given the success of the KMAX helicopters in Afghanistan. KMAX was designed by Lockheed Martin and Kaman Aerospace. It was the first unmanned helicopter designed and certified for external airlift operations. KMAX was originally deployed to Afghanistan as a trial of concept for delivering cargo to forward troops. As the program was successful, it continued to serve the logistics operations in the battlefield until 2014. During its stay in Afghanistan, it delivered more than 3.2 million tons of cargo and flew thousands of missions. According to Lockheed Martin [30], KMAX preserves the soldiers' lives by reducing the number of truck re-supply convoys and troop escorts, which are frequent targets of IEDs and insurgent attacks. KMAX has a cargo carry payload of 6,000 pounds and could airlift up to 5,600 pounds of cargo at 5,000 ft. The helicopter utilizes an under-slung method to carry cargo, which could be unloaded to forward troops while hovering in the air. Figure2.7 shows an example of KMAX Helicopter.

Sikorsky joined the development by announcing in May 2014 that it would convert a Black Hawk helicopter into a UAV with strength to lift up to 9,000 pounds of cargo with high cruise speed. Under the Matrix Technology and Manned/Unmanned Resupply Aerial Lifter (MURAL) program, in collaboration with the U.S. Army, the system is currently in the proof-of-concept phase [24].

Airship Cargo UAV

The last category of cargo UAV provides the largest cargo space and is the largest platform among the UAVs offered. This type of UAV was originally developed to match the cargo ships and aircraft capabilities.

The Aeroscraft is a vertical takeoff and hover airship and comes in two versions. The Aeroscraft ML866 is designed to carry up to 66 tons of payload, travel up to 3100 nautical miles and cruise at 100 knots. Aeroscraft ML868, a bigger version, is designed to carry up to 250 tons of payload and travel up to 5100 nautical miles. In comparison, cargo aircrafts such as C-17 and Antonov-225 could carry up to 75 tons of and 200 tons of cargo respectively [31].

According to Aeros [31], has the capability to stay afloat or hover, similar to an air balloon without exerting downward pressure to keep it afloat. With this capability, the Aeroscraft

Figure 2.7: KMAX Helicopter (Reprinted from [30])

could stay afloat, lower its cargo to the ground, and unload before moving to the next destination. In another words, there is no need to land at the airbase before unloading any cargo.

The program was initially contracted as part of Project Walrus, collaboration between Aeros, NASA, DOD, and DARPA. It was canceled due to failures in immature technologies such as hovering systems. It was eventually reverted to a technology demonstrator program, as part of Project Pelican in 2010 [32].

In 2012, Aeros [31] successfully completed a flight test, as part of Project Pelican, to prove its airworthiness, which is a process to test the safety and technology before transiting to serial production. Serial production is expected to start in 2016, with operational flight tests by 2020. Currently, the ML866 is offered to the military for medical supplies transportation, humanitarian assistance, or logistics resupply. The ML868 version is mainly offered for commercial use. Figure 2.8 shows a design of the Aeroscraft.

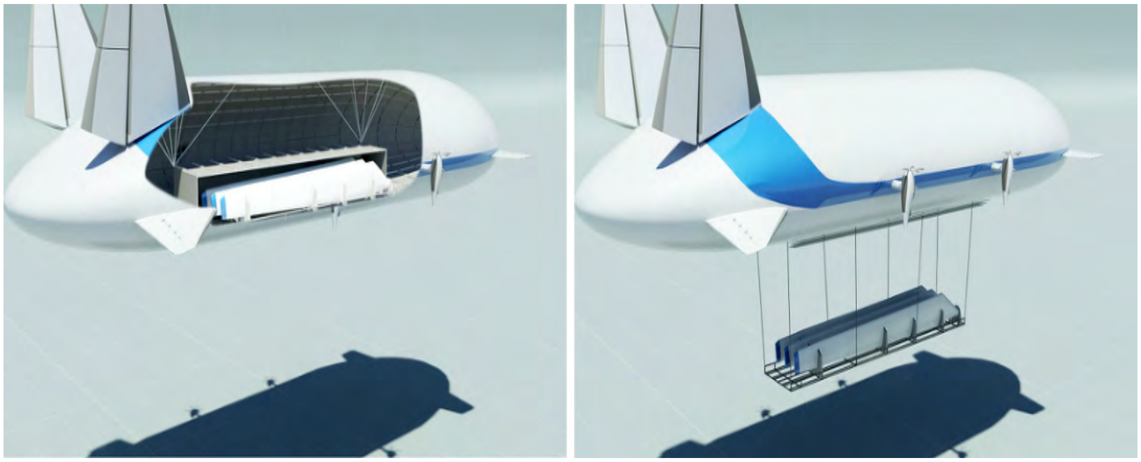

Figure 2.8: Aeroscraft Cargo UAV (Reprinted from [31])

2.4.3 EAB Logistical Demands

The logistics demand of an EAB is divided into four broad categories. They are namely food, water, aircraft parts, and fuel. These are the essential supplies used to support the whole operations of an EAB. The estimated consumption rates of each consumables each EAB are shown in Table 2.2, and the details are explained in the following subsections

Types		Est. Amount	Total Demands (lbs per day)
Food		100 URE or MRE a day	200
Water		3,500 gallons a day	28,000
Fuel	F-35	9,500lbs a mission	180,000
	Fire-Scout	500 lbs a mission	2,400
	AEW	3,000 lbs a mission	6,000
Parts		10% a month	500

Table 2.2: Demands of each Expeditionary Air Base by Type

Food and Water

Food and water are necessities required to feed the personnel in the EAB. An EAB has about 55–100 personnel. They include technicians maintaining the aircraft and runway, the pilots operating the aircraft and the camp commands to support the security, administration, and operations in the base.

The notional likely composition of personnel operating in each EAB is shown in Table 2.3

Team	**Number of personnel**
Aircraft Maintenance and runway operators	35-60
Pilots	10-20
Security, Admin and Camp Command	10-20
Total	55-100

Table 2.3: Personnel Composition of each Expeditionary Air Base

A research report documented [33] the demands of the FOBs and recommended solutions for a sustainable FOB. Interviews were conducted with logisticians and commanders serving in FOBs located in Afghanistan. The report studied aspects, such as food and water, fuel consumption and elements of planning and sustenance, affecting the FOBs and consolidated useful information regarding logistics demands and supplies of the FOBs.

Noblis [33] states that a FOB operates up to 6 months in the operating theater and has about 50 to 500 personnel. Because elaborate kitchen and storage facilities are unlikely to exist in FOBs, Meal, Ready to Eat (MRE) and Heat and Serve Utilized Group Ration (UGR) food packages are the recommended food for the FOBs. Both types are self-contained food packages, which provide a day's equivalent of food required for a soldier. A standard pallet of 49"L x 41"W x 49"H contains 500 meals and weighs about 1,000lbs.

Water supplies are used for drinking, preparation of food, maintenance of equipment and washing up. Noblis [33] estimates that 1750 gallons of water are used per FOB per day and recommends water supplies from wells or bottled water. Either water supplies are obtained from host nations, distillation from lakes, or potable water delivered from MOB to the FOB.

To obtain water from the host nation, the EAB needs to construct facilities and pipelines to connect to the water sources. This option is not recommended since, by design, an EAB has to be set up within three days and there is insufficient time and space to build such facilities. Furthermore, building of facilities before any operations would expose the locations of the EAB, which eventually become hot targets for adversaries to target. Finally, the EABs are located near dirt roads, highways, and rural areas. Building up facilities to these obscure

locations is not cost-effective for such short-term operations. To ensure sufficient water supplies are delivered to the FOB, it is recommended that supplies come from the MOBs with UAVs or trucks transporting by air or land the water supplies into the FOB.

Converting into the EAB demands, each EAB houses up to 100 personnel and would require 100 meals a day. Henceforth, MREs or UGR food supplies, and water were assumed to be delivered from the MOB to the EABs using either UAVs or trucks. With each gallon is equivalent to eight pounds of load, the minimum supply required

Fuel Consumption

An EAB is designed to house six F-35B, two Fire-Scouts and two AEBs. Insights from experimentations conducted by SEA-20B [5] shows that ten F-35B aircraft are required to patrol around the clock to provide fast reaction to deter adversaries flying towards the Spratly Islands. To provide early detection of surface assets, two Fire-Scouts are recommended to provide round-the-clock surveillance. In the experiment, each F-35B aircraft mission operates about 1.5 hours to 2.0 hours per flight, up to three flights a day. A Fire-Scout mission is expected to last about five hours per flight, with up to three flights a day. A typical F-35B aircraft consumes about 800 gallons of fuel per flight-hour, whereas a Fire-Scout consumes 100 lbs. of fuel per hour. Converting the mission criteria into fuel consumption demands, an F-35B aircraft would need 9,600 lbs. of fuel (8 lbs. per gallon) per mission whereas the Fire-Scout consumes 500 lbs. of fuel per mission. for 100 personnel would amount to 28,000 lbs. of water and 200 lbs. of meal per day.

Parts Consumption

According to U.S. Marine Corps Warfighting Publication (MCWP) 3.21.2 - Aviation logistics [34], there are two support packages established for aviation units. The packages are (1) local support package to support or meet ship's specific needs, and (2) Fly-in Support Packages (FISP) to support the squadron's aircraft detached from the CVN ship. The FISP contains parts required to perform Organizational level maintenance for a specific duration. Typical parts required for organizational level maintenance are Line Replaceable Units (LRUs) that could be removed and replaced at field level to restore the item to an operational ready condition. Typical LRUs in an aircraft includes the radar processing units, weapon processing units, etc. It is estimated that about 10–20% of aircraft parts are required to sustain an aircraft for 30 days of operations. This translates to about 500 pounds

of parts per day for the aircraft in the EAB.

2.5 Effects of the Logistics Concept

The logistics concept was defined in this chapter, with this thesis recommending Cam Ranh Bay and Subic Bay to serve as MOBs operating in the Vietnam and Philippines region respectively. This thesis adopted the MALSP II methodology and it recommends the use of cargo UAVs as the main transportation means to deliver the cargo to the EABs. To understand the effects of this logistics concept, the following chapters describe the methodology and models used in this thesis.

Due to scope of this thesis, the study of the full supply chain, from the parent node to the EABs, was not done in this thesis. The methodologies and models developed could be expanded to include the ESBs and PMALs for future studies.

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CHAPTER 3:
Methodology

3.1 Development Approach

To understand the logistics concept, a Discrete Event Simulation (DES) is developed to simulate the logistical process from the MOBs to the EABs. The development takes a two-stage approach to study the logistics concept proposed in Chapter 2.

The first stage develops an optimization model to determine the optimal transportation fleet size and mix for transporting the cargo to the EABs. Using homogeneous vehicles, i.e., the vehicles have the same characteristics, the results generated is injected into the DES runs to ensure the optimization model meets the turn-around time, as stipulated as a requirement in Chapter 2. An iterative process is performed to tune the optimization models until the outputs are able to meet the requirement. For example, this thesis uses the optimization model to find the optimal fleet size for the fixed wing cargo UAV. The DES is run with the results from the optimization mode to determine the feasibility of the model, by ensuring the turnaround time is below three days. Some of the results were unable to meet the requirement since the optimization model lacks the ability to include stochastic data as part of the calculation. Due to the differences in the stochastic behavior of a DES model, the optimization model is tuned to achieve the desired results. This is done iteratively together with the simulation, until it meets the requirements. This process is repeated for every platform recommended.

After tuning the optimization model for the homogeneous vehicles, a heterogeneous mix and match optimization is performed. This means that the data of all the different UAVs are inserted into the optimization model. The optimization model recommends the optimal fleet size and mix for use in our studies.

After the optimal solution is found, the second stage runs the DES to generate the results for analyzing the cost of operations, the amount of supplies to use and the performances of the UAVs against convoy trucks. Figure 3.1 illustrates the phases of development.

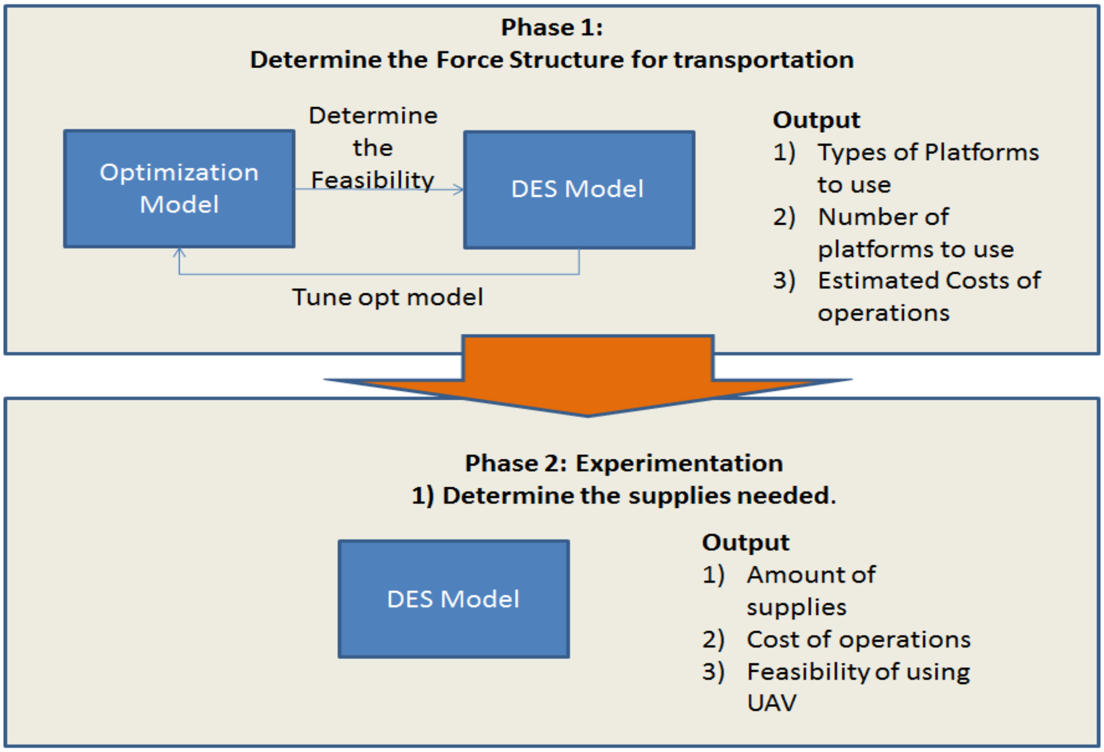

Figure 3.1: Phases of Development

3.1.1 Vehicle Routing Problem

One of the questions of this thesis is to define the force structure of the logistical team. The main aim is to find the optimal fleet size and mix to support the logistics operations. In this thesis, three aircraft types were used. Each aircraft, which we also refer to as a vehicle in the model, has distinct characteristics. For example, each vehicle has its set of maximum capacity, speed, operating distance, cost etc.

To save costs, we aim to optimize the cost of operations. The cost of operation is divided into fixed costs and variable costs. The fixed cost is the cost of acquiring an aircraft. The variable cost is associated with the cost of flying an aircraft for a mission. Flight cost is defined as total flight hours $\times$ flight cost per hour.

In the operational theater, the aircraft could be ordered to traverse through several camps to fulfill the EABs' demands before returning to the base camp. For example, Aircraft A, which could carry 10,000 pounds of goods, could be asked to deliver 3,000 pounds to

EAB1 and 7,000 pounds to EAB2 before returning to base camp. The route constructed would hence be (0,1) to (1,2) to (2,0). We refer to these routes as a collection of arcs (i, j). This route is a key component to minimize the flight costs, since a longer route leads to higher flight hours. A short route could minimize flight hours, but might require more aircraft to support the operation. Hence, an optimal route is required.

The Vehicle Routing Problem (VRP) is one of the famous optimization problems used to plan a set of optimal routes which minimizes the operational costs, while ensuring the customers' demands are met [35], [36]. The original problem was used to determine a set of optimal routes for a fixed set of vehicles delivering goods to multiple customers, spread across disparate locations [35], [36]. The model has since evolved to solve problems to find the optimal fleet size, trips, capacity of vehicles, fleet mix, etc. [35], [36]. Of particular relevance to this thesis are the following related works.

Lee and Huang [37] developed the multi-trip VRP model together with the distribution center location problem. The approach uses a fixed set of vehicles to perform multiple delivery trips. A heuristic approach was developed in three phases to determine the optimal solution. First, the initial warehouse locations and routes were defined. The second phase uses the simulated annealing logic, which follows the methodology of annealing metal. When temperature is high, there is more variability and flexibility. This means there are more possibilities of finding solutions to a problem. When the metal gradually cools, the structure becomes fixed. Thus, a solution close to the optimal solution is found. The third phase improves the location of warehouse found in phase two by comparing solutions found in phase two. Chang and Sian [38] developed a VRP with multiple trips and time windows (MTTWVRP), to minimize the number of vehicles and their delivery time. First, the customers' demands are clustered into time windows, according to the customer's desired time. This is done to generate an optimal set of servicing windows. Next, they optimized the number of vehicles, which could perform multiple trips, required to serve each servicing window By combining both solutions, a time-based vehicle dispatch schedule was formed. Noorizadegan et al. [39] developed a capacitated VRP to study a Heterogeneous VRP when customers' demands are uncertain. It uses a Mixed Integer Linear Program (MIP) to formulate a VRP model. In this model, heterogeneous vehicles are used to transport goods to the customers Heterogeneous means each vehicle type has distinct characteristics, such

as capacity, speed, maximum distance traveled, etc. Using a VRP model, the optimal fleet size and types were determined. Dell'Amico et al. [40] developed a heuristic approach to determine the composition of vehicles given a fleet of heterogeneous vehicles to serve a set of customers within a time-frame. Using a Fleet Size and Mix VRP with Time Windows, an optimal fleet composition, i.e., the fleet size and types, was found to transport goods to its customers within a certain time window.

VRP Model

Each vehicle used has a limited capacity. The vehicles are expected to take multiple trips before replenishing the full demand of the EABs. Secondly, the aim of this thesis is to find the optimal fleet size and the types to transport the cargo. Thus, this thesis developed a Multi-trip, Fleet Size and Mix Vehicle Routing Optimization model. Multi-trips means a vehicle is allowed to perform several trips within a day to deliver goods to the customers. Fleet Size and Mix means the VRP model finds the optimal number of vehicles to use and the types of vehicles to use.

Development Tool

The development of the VRP model is modeled using Generalized Algebraic Modeling System (GAMS) tool. GAM is a program developed by GAMS Development Corporation. It is designed for setting up and solving mathematical programmed optimization models. GAMS allow users to specify complex problems in mathematical structures and data types. The complex problems could be resolved by modeling linear, non-linear or mix-integer optimization problems in GAMS. The problems are specified in mathematical equations and GAMS will solve the model, while allowing users to change the formulation quickly and perform sensitivity analysis [41].

3.1.2 Discrete Event Simulation

The DES is a simulation approach used to model the real world situations. A DES model consists of a network of activities described by events and states. A state describes a variable, which affects a system. An event is an intention to change the state or activities of the system. For example, a state could be the number of servers available to serve a customer. When a customer arrives, i.e., an arrival event, the server serves the customer and the number of available servers decreases. When all the servers are occupied, a queue (another

state) will form. Henceforth, each activity is triggered by an event, which could eventually change a state variable.

The main advantage of DES is its ability to represent the uncertainty of a system, thus, providing a realistic representation of the real world. This method is found to be more effective and faster than running a continuous time-based simulation. [42]. The following shows the related works, which are applicable for our thesis.

Foong [43] developed a DES model to analyze airlift operations for delivering humanitarian supplies from the base camps to the disaster stricken sites. The model simulates the different stages of the operations. The first stage involves the preparation of the cargo and transportation from a holding area to the landing spot. The second stage simulates the transportation of the cargo from the landing spot to the targeted area. These cargo is either airdropped or unloaded to the target site. Seagren and Hancock [8] developed a DES model to analyze the aspects affecting the supply chain of the MALSP doctrine. As described in Chapter 2, MALSP supply chain includes several nodes between the supply bases and the Forward Operating Base (FOB). The model utilizes a generic algorithm to generate the demands for each node of demands. Using a parent-child node demand-supply algorithm, the parent node first satisfies the demands of the child node, by issuing and delivering a part to the child within a stipulated period [8]. After the parent node issued the part, it in turns orders a replacement part to replenish the outgoing stock. The entire chain of events describing the activities within the MALSP process was simulated in the model.

Logistics DES Model

This thesis develops a DES model to simulate the process of logistics transportation. This model simulates the flow of events and the states transitions between the MOBs, the EABs and the aircraft platforms used in the logistics supply process. In addition, the model is used to generate and record the results of the logistics process, which is eventually used for analysis.

Development Tool

The DES is modeled using SimKit, a Java program developed at the Naval Postgraduate School. Simkit aids in implementing a component-based simulation model. An Event graph is generally the methodology used to describe the relationship between three el-

ements of the model. The elements are (1) state variables, (2) the events changing the state variables, and (3) relationships between events, depicted by an arrow (also known as edge) [42].

Every process in the model exchanges messages called events. An event contains a timestamp that specifies when the event will occur. Once an event is called, it could change a state variable to effect a change in the system parameters. The flow and direction of the event is illustrated by an arrow from the origin event to the designated event. Sometimes, a time delay is added to simulate the delay between each activity [42]. Figure 3.2 illustrates a typical event graph. The events that are triggered in the system are illustrated by a circle. The state variables affected by the event are described below the events. After an event has occurred, it triggers the next event in queue and sends an object, marked by a rectangular box, which could affect the next event. For example, the logistics load sent by Event A is sent as an object to Event B. Event B receives the object and processes it to change the state variable accordingly. To describe the time delay between events, a time delay is illustrated.

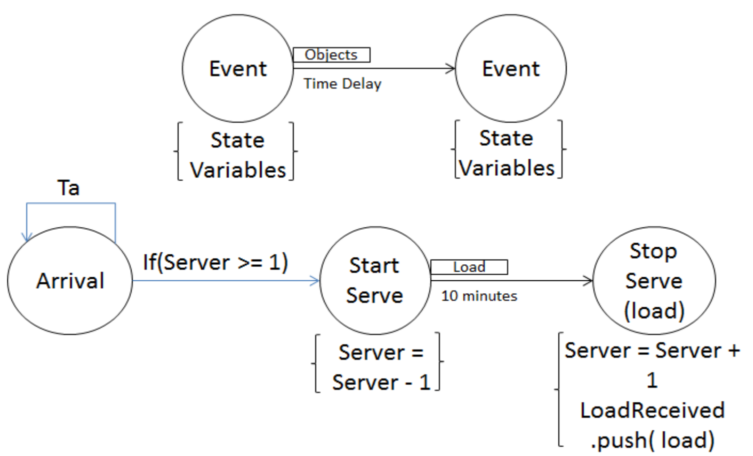

Figure 3.2: The top figure shows a typical event graph. The bottom figure shows an example of an event graph.

In Figure 3.2, an example is shown to illustrate an event graph. A customer arrives at random time interval, *Ta*, and needs to send a parcel. When there is an available server, the server begins to serve the customer. To signal the start of service, a `StartService` event is queued.

In the `StartService` event, the server state variable is decremented to note the decrease

in the number of available servers. As it takes ten minutes to serve the customer, the time delay is marked in the event graph to illustrate the time delay. The load information is inserted to `StopServe` event and queued.

After ten minutes, the `StopServe` event is triggered to signal the completion of the service. The server ends the service and insert the load information into its information list, i.e., `LoadReceived`, which is also a state variable. The server state variable is incremented to note the increase in number of available servers.

Development Works

The next few chapters provide more details on the models developed, the experiments conducted, and the analysis of the results. Chapter 4 describes the development of the optimization model and Chapter 5 describes the development of the Discrete Event Simulation. The experiment runs and results analysis is described in Chapter 6.

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CHAPTER 4:
Vehicle Routing Problem Model Formulation

4.1 Objectives

In this thesis, employment of three types of aircraft is explored. Each aircraft, which we also refer to as a vehicle in the model, has distinct characteristics. For example, each vehicle has its maximum capacity, speed, operating distance, cost, etc. The whole aim is to ensure the EABs' demands are met while ensuring the cost of operation is minimized. The cost of operation is divided into fixed costs and variable costs. The fixed cost is the cost of acquiring an aircraft. The variable cost is associated with the cost of flying an aircraft for a mission. (Flight cost is defined as flight hours $\times$ flight cost per hour). To save cost, an optimization model is used to determine the minimal cost of operations while ensuring the demands of EABs are satisfied.

In the operational theater, the aircraft could be ordered to traverse through several camps to fulfill the EABs' demands before returning to the base camp. For example, Aircraft A, which could carry 10,000 pounds of goods, could be asked to deliver 3,000 pounds to EAB1 and 7,000 pounds to EAB2 before returning to base camp. The route constructed would hence be (0,1) to (1,2) to (2,0). We refer to these routes as a collection of arcs (i, j). The route is a key component to minimize the flight costs, since a longer route will lead to higher flight costs. A shorter route could minimize flight costs, but might require more aircraft to support, which invariably increases the fixed cost. Thus, the Vehicle Routing Problem Optimization model is used.

The following assumptions are made:

1. Different vehicle types, with different capacity, can perform multiple trips in a day.
2. Every vehicle starts from the base camp and returns to the base camp after each trip.
3. The base camp has unlimited supplies and no shortages occur.
4. No sub-tour is allowed. In other words, nodes within each trip have to be sequential, and secondly the end node has to be the start node of the next node, e.g., (0,1) to (1,3) to (3,2) to (2,0).

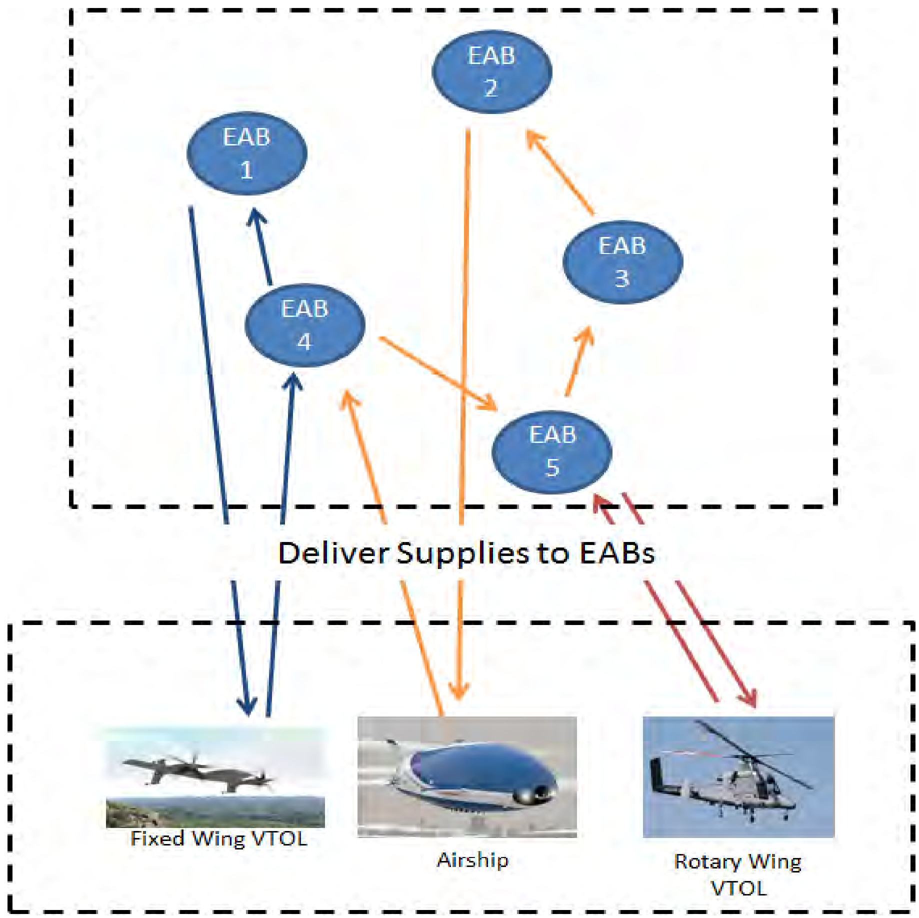

Figure 4.1: Vehicle Routing Problem Model. This figure illustrates the variability of routes that each vehicle could serve. It also illustrates that each EAB could be served by several vehicles to fulfill its demands.

5. The route constructed cannot exceed the number of nodes available.
6. If the capacity of the vehicle is more than the demand, the vehicle can traverse between different EAB nodes to deliver supplies to multiple EABs. However, each EAB can only be visited once per trip.
7. Each EAB is located at a different site and demands a fixed amount of supplies.
8. All demands have to be fulfilled within a stipulated time.
9. No fixed time window is required. That means the aircraft can deliver the supplies at any time of the day.
10. The cargo load carried by the aircraft cannot exceed the aircraft maximum capacity.
11. Each aircraft cannot fly beyond its maximum operating distance.

4.2 Parameters and Decision Variables

4.2.1 Parameters of the Optimization Model

Table 4.1 shows parameters of the optimization model. The data sources and data used for the experimentation are described in Section 6.1.3.

Parameters	**Units**	**Description**
N	-	Total number of EAB
i, j	-	Index of nodes, $i, j = 0, 1, 2, 3..., N$ $i = 0$ and $j = 0$ defines the base camps nodes and $i, j > 1$ defines the EABs
h	-	subset of i, $h = 1, 2, 3..., N$ h defines the EAB nodes
k	-	Type of aircraft $k = 1, 2, 3, 4$ 1 - airship 2 - rotary wing aircraft 3 - fixed wing aircraft 4 - trucks
l	-	Index of vehicle, $l = 1, 2, 3..., L$
r	-	Index of trip, $r = 1, 2, 3, ..., R$
cap_k	Lbs.	Maximum capacity of each aircraft type k
$costHour_k$	USD	Cost of flying the aircraft type k per hour - inclusive of fuel and crew maintenance
$costAC_k$	USD	Cost of aircraft type k
d_j	Lbs.	Demand of each EAB
$dist_{ij}$	Miles	Distance between each node (i, j)
$speed_k$	Miles/Hr	Average speed of aircraft type k
M_{Qty}, M	-	Large arbitrary numbers
$loadPrepTime$	Mins/Lbs.	Average time to load and unload each pound of cargo into the aircraft and time to prepare the cargo in the warehouse.
$tripPrepTime$	Mins	Average time to prepare the aircraft for each trip
$MaxLogTime$	Mins	Maximum turnaround time to deliver all demands to the EAB

Table 4.1: Parameters of the Optimization Model

Key Parameters

The aim of the optimization model is to minimize the cost of operations while ensuring the supplies are delivered within the turnaround time. To simplify the optimization model, this thesis simplifies the formulation into two key parts.

The first part is to ensure the turnaround time, referred as *MaxLogTime*, is achieved. This criterion is achieved by only considering the warehouse preparation time and total flight time to estimate the turnaround time. An example is shown in Figure 4.2. It takes one airship to travel three trips, and one rotary wing aircraft to travel two trips to complete the request of an EAB. The *loadPrepTime* is an estimate of the throughput to prepare the load. Thus, the total turnaround time is the total time to prepare and deliver the supplies to the EAB.

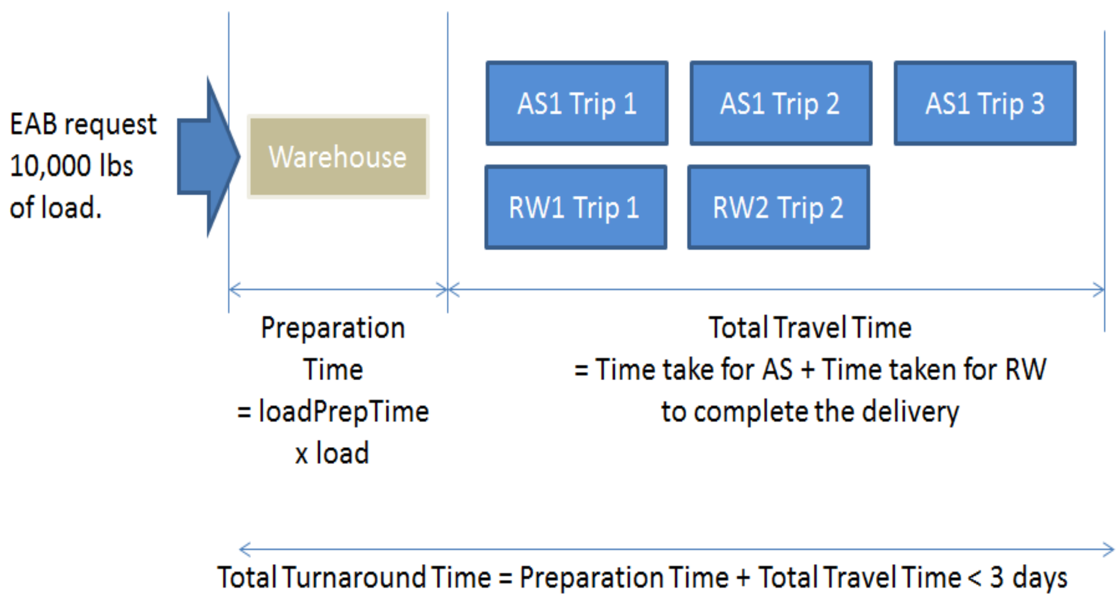

Figure 4.2: This figure shows the turnaround time for delivery. The total time to complete a request consists of the time to prepare the supplies in the warehouse, and the time to deliver the supplies to the expeditionary airbase. The total time to prepare and deliver must be within three days. In this figure, AS refers to an airship, whereas RW refers to a rotary wing aircraft.

The second part is determining the cost of operations. Note the number of platforms, the number of vehicles, and number of trips required to deliver the supplies in Figure 4.2. The number of vehicles provides an estimate to the acquisition costs. The amount of travel time provides an estimate on the cost of operating the trips. Thus, the total cost of operations is

the total cost of acquisition and total cost of the operating the trips.

The other parameters, such as maximum capacity and maximum speed, are added to the optimization model to bind the model to operate within the constraints of the aircraft characteristics.

4.2.2 Decision Variables

Table 4.2 shows the decision variables of the model. x_{ijklr} indicate if the arc (i, j) will be served by vehicle number l type k on trip r. q_{ijklr} indicates the quantity carried by the vehicle number l of type k from node i to node j on trip r. V_{kl} indicates if the vehicle type k of vehicle number l is activated. $Tjklr$ indicates if node j is activated by vehicle klr. V_{kl} and x_{ijklr} are binary decision variables, which means that 1 - Activated and 0 - Not Activated

Variable	Description
x_{ijklr}	Activation of Aircraft type k flying from node i to node j on vehicle number l of trip r x ={0,1}
q_{ijklr}	Quantity carried by Aircraft type k flying from node i to node j on vehicle number l of trip r q = *integer variable*
V_{kl}	Determine if index l of vehicle type k is activated V ={0,1}
B_{klr}	Determine if the trip is activated B ={0,1}
T_{jklr}	Determine if node j is traversed by Vehicle klr T ={0,1}
dis_{hklr}	Determine the total distance traveled by each vehicle to deliver the cargo to the EAB in each trip klr $dis = integer\ variable$
z	Objective function of model (Total cost of operations) $z = free\ variable$

Table 4.2: Decision Variables of the Optimization Model

4.3 Optimization Model

Mixed Integer Programming (MIP) is used in this optimization model. A mixed integer-programming problem is used where some decision variables are restricted to integer values, i.e., 0,1,2,3, etc. For instance, in this model, q is an integer variable which describes the amount of goods carried across each arc (i, j). Whereas the other variables, such as x, B and V, are discrete variables, i.e., restricted to $0, 1$, to determine if the particular route, trip, and vehicle type are all activated.

4.3.1 Objective Function

The optimization model begins with an objective, which is to minimize the total cost of operations. The cost of operations includes (1) fixed aircraft costs and (2) variable costs dependent on the flight hours.

1. The fixed costs is determined by the number of aircraft purchased. V_{kl} refers to the number of vehicle type k acquired to support the operations. Total cost of aircraft type k purchased = cost of aircraft type k $\times$ number of vehicles activated.
2. The variable cost is determined by the cost of flying from node i to node j. The variable cost refers to the cost of flying the aircraft (Total flight hours $\times$ Cost of Flying per hour). Cost of Flying per hour refers to the average cost incurred, inclusive of the maintenance, pilots, and fuel costs, to operate an hour of flight.

Based on the above, the objective of minimizing the total cost of operation, z, is given by:

$$z = \sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{K}\sum_{l=1}^{L}\sum_{r=1}^{R} x_{ijklr} \times costFly_k \times dist_{i,j}/speed_k + \sum_{k=0}^{K}\sum_{l=1}^{L} V_{kl} \times costAC_k \tag{4.1}$$

4.3.2 Constraints

To determine the minimum cost of operations, constraints are added to bind the objective, in order for the optimization tool to calculate the optimal result. The following are the constraints and conditions added to the optimization model.

Conditions to ensure the demands are met and within vehicle constraint

The total of the cargo delivered should be more than the EAB's demand.

$$\sum_{i=0}^{N}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{r=1}^{R} q_{ihklr} \geq d_h \qquad \forall\, h \tag{4.2}$$

The quantity delivered per node should be activated only when the node is activated. A large number is assigned to ensure the quantity does not exceed the maximum capacity.

$$q_{ihklr} \leq M_{Qty} \times x_{ihklr} \qquad \forall\, i,h,k,l,r \tag{4.3}$$

The total load carried by the vehicle during the trip should not exceed the vehicle's capacity.

$$\sum_{i=0}^{N}\sum_{h=0}^{N} q_{ihklr} \leq cap_k \qquad \forall\, i,h,k,l,r \qquad where(i \neq h) \tag{4.4}$$

Each arc (i, j) is only activated if the trip is activated, that is,

$$x_{ijklr} \leq B_{klr} \qquad \forall\, i, j \tag{4.5}$$

Each trip is only being activated if the vehicle is activated, such that:

$$B_{klr} \leq V_{kl} \qquad \forall\, k,l,r \tag{4.6}$$

A check to determine if node j is traversed by Vehicle klr is given by

$$T_{jklr} \leq \sum_{i=0}^{N} x_{ijklr} \qquad \forall\, j,k,l,r \tag{4.7}$$

Additionally, recall from our previous list of assumptions, no sub-tours are allowed, i.e.,

the vehicles are not allowed to move to the same node more than once.

$$\sum_{i}^{N}\sum_{h}^{N} x_{ihklr} \leq N \qquad \forall\, k,l,r \tag{4.8}$$

The total distance of the trip should not exceed the aircraft maximum flying range, or in other words,

$$\sum_{i=0}^{N}\sum_{j=1}^{K} x_{ijklr} \times dist_{ij} \leq maxDist_k \qquad \forall\, k,l,r \qquad where(i \neq j) \tag{4.9}$$

The total time of delivery must be within a stipulated time constraint. The total time of delivery include (1) time for aircraft to travel from node to node, (2) time to prepare the supplies and (3) time for warehouse to prepare the cargo and time to load and unload cargo. These constraints are illustrated in Equations 4.10 and 4.11 provides the details on the distance traveled for each trip. Equation 4.12 shows the constraint of turnaround time.

$$dis_{hklr} - \sum_{i=0}^{N}\sum_{j=0}^{N} x_{ijklr} \times dist_{ij} \leq maxDist_k \times (1 - T_{jklr}) \qquad \forall\, h,k,l,r \tag{4.10}$$

$$dis_{hklr} - \sum_{i=0}^{N}\sum_{j=0}^{N} x_{ijklr} \times dist_{ij} \geq 0 \qquad \forall\, h,k,l,r \tag{4.11}$$

$$\begin{aligned} \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{r=1}^{R} dis_{hklr}/speed_k + \sum_{i=0}^{N}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{r=1}^{R} q_{ihklr} \times loadPrepTime \\ \leq maxLogTime \times \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{r=1}^{R} T_{hklr} \qquad \forall\, h \end{aligned} \tag{4.12}$$

Conditions to ensure the trips and vehicle numbers are sequential

The trip number r has to be sequential, from [37]

$$\sum_{j=1}^{N} x_{0jklr} > \sum_{j=1}^{N} x_{0jklr+1} \qquad \forall\, k,l,r \qquad where(r < R) \tag{4.13}$$

The vehicle number l has to be sequential, from [37].

$$\sum_{j=1}^{N} x_{0jklr} > \sum_{j=1}^{N}\sum_{h=0}^{N} x_{0jkl+1r} \qquad where(l < L) \tag{4.14}$$

Flow Conservation

The flow conservation constraints help to form the routes by listing the constraints.

Each vehicle has to start and end at the base camp, represented by constraint 4.15.

$$\sum_{j=1}^{N} x_{0jklr} = \sum_{i=1}^{N} x_{i0klr} \qquad \forall\, k,l,r \tag{4.15}$$

The start and end nodes of each arc must not be the same node, i.e., the vehicle has to move to a different node after delivering the goods.

$$x_{iiklr} = 0 \qquad \forall\, i,k,l,r \tag{4.16}$$

The start of an arc has to be the exit point of the previous arc. For example, traveling from (i,h) to (h,j). h defines that the start node h is the exit node h from the previous arc. B_{klr} represents the trip activated by the vehicle number l of type k.

$$\sum_{i=0}^{N} x_{ihklr} - \sum_{j=0}^{N} x_{hjklr} \leq B_{klr} \qquad \forall\, h,k,l,r \qquad where(i \neq j \neq h) \tag{4.17}$$

Each trip should start from the base and end in the base. This means the starting arc of the trip will originate from the base and ending arc will end at the base. These arcs are

activated only when the trip is activated.

$$\sum_{j=1}^{N} x_{0jklr} = B_{klr} \qquad \forall\, k,l,r \tag{4.18}$$

$$\sum_{i=1}^{N} x_{i0klr} = B_{klr} \qquad \forall\, k,l,r \tag{4.19}$$

Finally, each node can only be accessed once per trip, which defines constraint 4.20 for B_{klr} representing the activation of the trip is assumed to be:

$$\sum_{i=1}^{N} x_{ihklr} + \sum_{j=1}^{N} x_{hjklr} \leq B_{klr} \qquad \forall\, h,k,l,r \tag{4.20}$$

4.3.3 Optimization Model Software

Software, including source code, and associated documentation can be found at "`http://faculty.nps.edu/thchung`" under "Resources, Software".

CHAPTER 5: Discrete Event Simulation

5.1 Conceptual Model

The conceptual model shows the high-level view of the interactions between the entities involved in the logistics resupply process. The process starts with the EABs consuming their supplies. Once the supply reaches the resupply trigger limit, the EAB requests the base camp to deliver the supplies. The base camp takes in the EAB's order and prepares the cargo before delivering to the airport. Once the cargo is delivered to the airport, the air command assigns an aircraft to deliver the supplies to the EAB. The designated aircraft flies to deliver the cargo to its designated EABs. At the end of the delivery, it returns to base and reports for the next mission.

The model is divided into three sub-models, namely `Base Camp Model`, `Consumption Model`, and `Air Transportation Model`. The `Base Camp Model` models the process of the logistics center, warehouse, and airport. The `Consumption Model` models the consumption behavior of the EABs. The `Air Transportation Model` models the behavior of the aircraft delivery. Figure 5.1 illustrates the conceptual model of the logistics resupply. The following sections provide more details on the model descriptions.

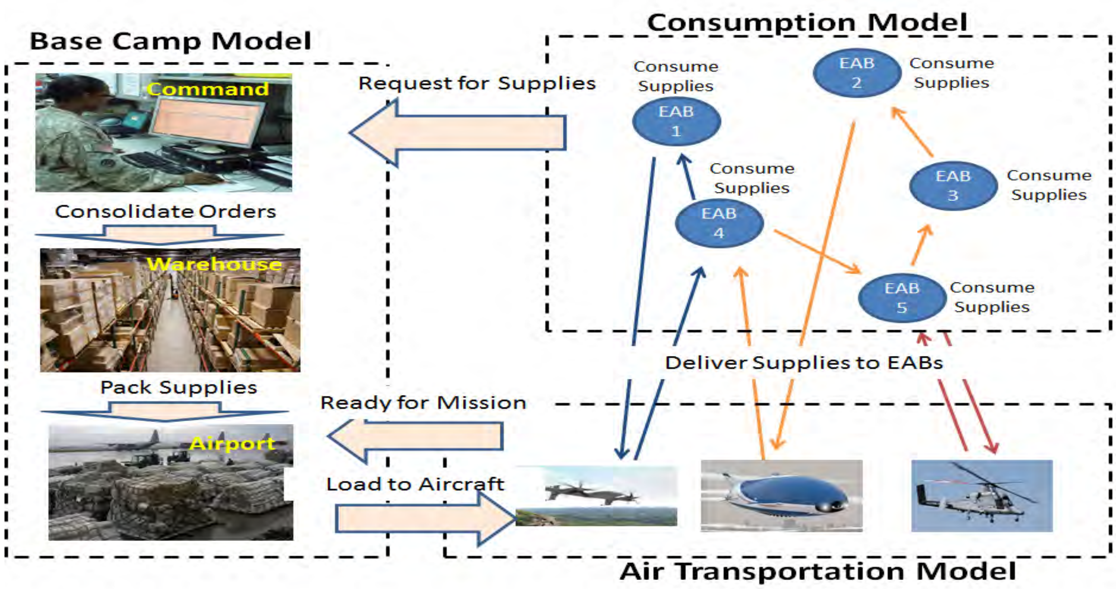

Figure 5.1: Conceptual Model of the Discrete Event Simulation

5.1.1 Consumption Model

The `Consumption Model` describes the typical consumption behavior of an EAB. Figure 5.2 depicts the process of the consumption.

In this process, a Just-in-Time concept is implemented. Each base carries sufficient supplies to last a number of days in the EAB, typically between seven to thirty days of supplies. The aim is to reduce the warehouse inventories and storage space, which effectively translates to lower storage and personnel costs.

In this model, each EAB consumes its supplies at a constant rate. When the supply reaches the trigger limit, e.g., three days of supplies left, the EAB immediately requests the base camp to resupply the EAB. To meet any unforeseen circumstances, such as delayed deliveries and overconsumption of supplies, additional three days of supplies are stocked up as reserves to meet any shortages.

As each order could be divided into several consignments–meaning several deliveries could be required to fulfill the request–the supplies are topped up whenever a delivery arrives. For example, consider when 1,000 lbs. of food are requested. The first trip delivers 400 lbs., the second trip delivers 400 lbs., and the third and final trip delivers 200 lbs.

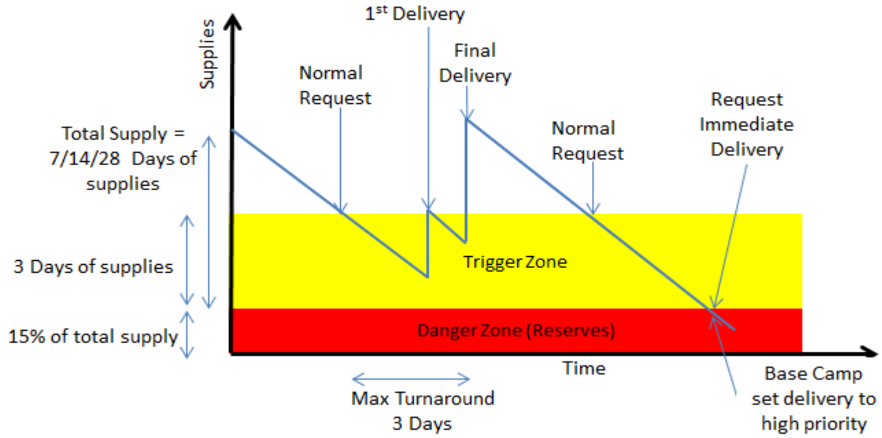

Figure 5.2: Consumption Process Model Overview

In the event of non-delivery, or a missed order, the EAB supplies would reach the danger zone, meaning it reaches the reserves level and there is a possibility that supplies might not be sufficient to sustain the camp. If that happens, an urgent request is sent to the base camp, allowing the base camp to set the delivery as high priority.

The sequence of events repeats itself for every consumption cycle. In this simulation, the supplies are divided into four categories, namely (1) food, (2) water, (3) parts, and (4) fuel. Each category of supply has different consumption rates.

5.1.2 Base Camp Model

The `Base Camp Model` models the events occurring in the logistics center. Figure 5.3 depicts the process of the base camp.

Each EAB requests its desired supplies, e.g., 1,000 lbs. of food, and 2000 lbs. of water, to the logistics center. The logistics center consolidates each order and priorities the requests according to their urgency level. After that, it keys in the order via the computerized system for the warehouse to prepare the orders.

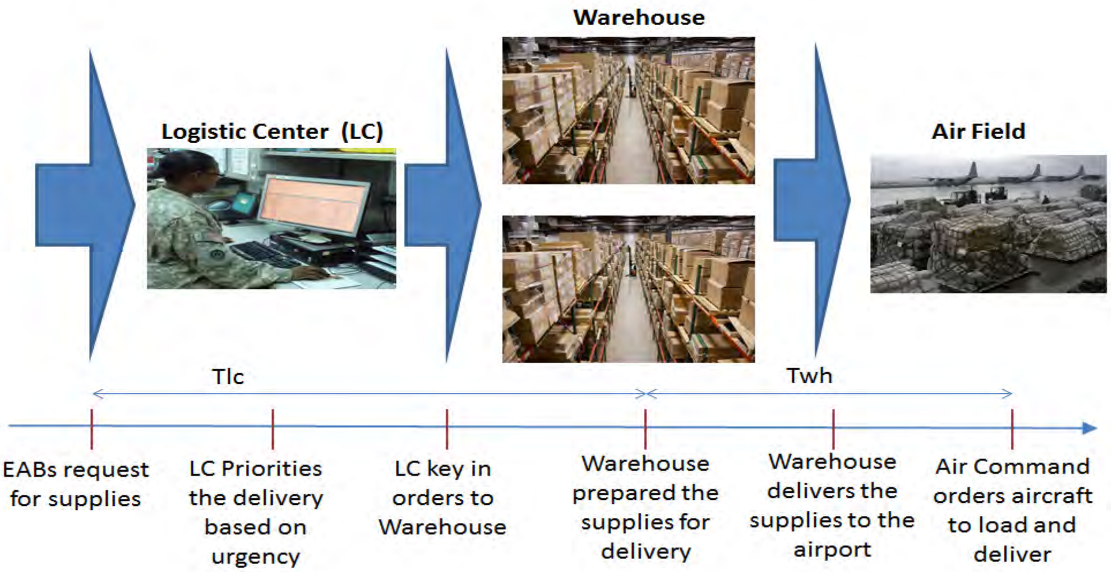

Figure 5.3: Base Camp Process Model Overview

In this model, it is assumed that multiple warehouses are available to prepare the orders. Each warehouse is capable of preparing the logistics at a certain rate, e.g., 1,000 lbs. per hour. If multiple orders arrive at the same time, the team prepares the order with the highest priority first before attending to the rest. Once the orders are prepared, the warehouse delivers the supplies to the airport.

In the airport, any aircraft that has returned to base and been maintained reports its availability to the air command. The air command does the planning and allocates the cargo to the available aircraft. To facilitate the planning, the allocation is based on a first-in first-out method, meaning the first available aircraft is chosen first to transport the goods to the EAB. To save costs, every aircraft has to be fully loaded before it could fly to its destination. The exception to this rule would be the prioritized orders. All prioritized orders are delivered as soon as possible and are loaded on the aircraft as soon as an aircraft is available. In the event that the aircraft is not fully loaded and no other prioritized orders are in the airport, the aircraft could depart to deliver its goods. Otherwise, it must wait until the aircraft is fully loaded before flying.

5.1.3 Aircraft Transportation Model

The `Air Transportation Model` describes the events associated with the aircraft. Figure 5.4 depicts the process of the air transportation process.

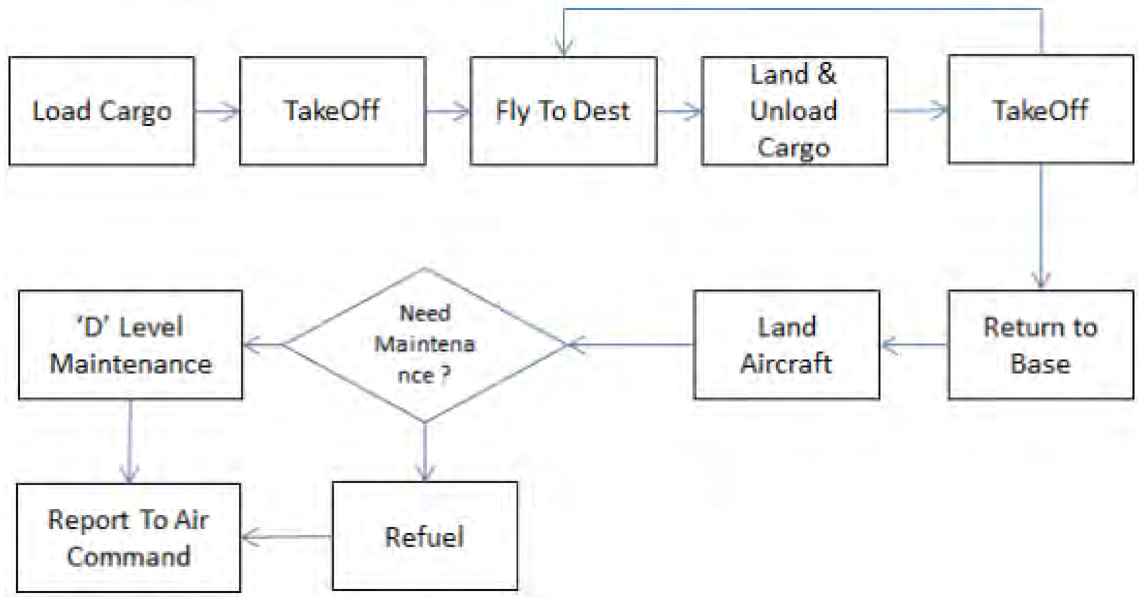

Figure 5.4: Air Transport Process Model Overview

The aircraft receives the orders from the air command to prepare for departure. The airport team first loads the cargo into the aircraft, according to the allocation provided by the air command. After it is loaded with the cargo, the aircraft takes off from the base and flies to its destination. Upon reaching the destination, the aircraft lands at the EAB and unload the cargo assigned to the EAB. Thereafter, the sequence is repeated until the cargo is delivered to all EABs. In the case of the airship, it hovers and lowers the cargo to the EAB.

After the cargo is delivered, the UAV returns to base and is checked by the maintenance crews. In the event that serious defects are found, the aircraft is sent for Depot ("D") level maintenance. Thus, it is not be available for delivery. "D" level maintenance refers to maintenance procedures that require specialized skills or equipment to conduct. These maintenances are usually performed in the aircraft carrier instead of in the forward bases. The time for "D" level repairs could be about eight hours. Otherwise, the aircraft is refueled and prepared for its next mission. The time to refuel an aircraft is about 15 minutes to an hour. Once maintenance is completed, the UAV reports to the air command for its mission.

5.2 Event Graphs of the Simulation

The Event Graphs of the simulation illustrates the events, state transitions and the objects passed between each event. For more description of the event graph, please refer to Section 3.1.2.

5.2.1 Simulation Entities Objects

The simulation entities objects are used to store the parameters and states of the cargo, aircraft, base camp, and consumables entities.

Aircraft Entity

The aircraft entity is an object that models the different types of aircraft. The parameters and states of the objects are defined to differentiate the aircraft types. The attributes used for the object are described in the Table 5.1.

Attributes	Variable	Description
aircraftId	int	Identification code of the aircraft
aircraftType	int	Type of Aircraft 0 - VTOL Rotary Wing 1 - Airships 2 - VTOL Fixed Wing
avgSpeed	double	Average Speed of the Aircraft (Miles /min)
maxCapacity	double	Maximum Capacity of the aircraft (lbs.)
loadingTimePerPound	int	Average Loading time onto aircraft. Defined in minutes per pound (Mins)
prepTime	double	Preparation Time for aircraft (Mins)
takeOffTime	double	Take off time for aircraft (Mins)
avgTimeToRefuel	double	Average time for aircraft to repair and refuel (Mins)
avgTimeTo HardMaintain	double	Average time for aircraft to perform Depot Level maintenance (Mins)
dest	int	Next Destination of the aircraft
currentCampId	int	Current campId where the aircraft has reached

Attributes	Variable	Description
loadMap	HashMap <Int, CargoLoad>	Hashmap mapping CargoLoad to campId

Table 5.1: Aircraft Entity Object

Consumables Entity

The consumable entity is an object that models the different types of consumables. The parameters and states of the objects are defined to differentiate the different types of consumables. The attributes used for the objects are described in Table 5.2.

Consumables Entity	Variable	Description
Type	EnumType	Type of Consumables 0 - Food 1 - Water 2 - Parts 3 - Fuel
baseLoad	double	Load required to sustain the EAB for a stipulated number of days (lbs.)
startLoad	double	Start Load of the consumables - Used for initializing the entity during every run (lbs.)
currentLoad	double	Existing load available in the EAB (lbs.)
consumptionRate	double	Average Consumption Rate of the EAB (lbs. per min)
requestedLoad	double	Load requests sent to base camp for resupply (lbs.)
baseReserves	double	Reserves required for the camp (lbs.)
triggerLimits	double	The limit before triggering the request (lbs.)

Table 5.2: Consumables Entity Object

CargoLoad Entity

The CargoLoad entity is an object that models the consignment intended for the receiving camp. In this consignment, different consumables types could be delivered. For example, the aircraft could carry different types of load within the same consignment. The parameters and states of the objects define the cargo delivered. The attributes used for the object are described in Table 5.3.

CargoLoad Entity	Variable	Description
campId	int	The destination of this package of load
food	double	Amount of food in this package (lbs.)
water	double	Amount of water in this package (lbs.)
parts	double	Amount of parts in this package (lbs.)
fuel	double	Amount of fuel in this package (lbs.)

Table 5.3: CargoLoad Entity Object

Camp Entity

The Camp Entity is an object that models the base camp and EABs. The parameters and states of the objects are defined to differentiate the different types of bases. The attributes used for the objects are described in Table 5.4.

Aircraft Entity	Variable	Description
campId	int	Identification code of the camp 0 - Base Camp 1 - EAB1 2 - EAB2 3 - EAB3 4 - EAB4

Aircraft Entity	Variable	Description
		5 - EAB5
mapcellX	int	Location of the camp in the X-Axis Map Allocation
mapcellY	int	Location of the camp in the Y-Axis Map Allocation
mapcellSize	int	Size of each map cell (Miles)
consumablesList	ArrayList <Consumables>	List of Consumables

Table 5.4: Camp Entity Object

5.2.2 Air Transport Process Event Graph

The `Air Transport Process` first instantiates the variable. The model follows a conveyor belt pattern, whereby after processing an event, the entity is passed on to the next event for processing.

The `Air Transport Process` event graph is responsible for modeling the stages of cargo delivery by the aircraft. The first stage processes the cargoes for loading to the aircraft and sortie the aircraft to fly to its destinations. Stage two models the delivery of the cargo to the various EABs. Stage three manages the activities after it reaches base.

In this event graph, the aircraft entity object manages the parameters and states. Upon reaching a decision event, the object transits its states accordingly.

Figure 5.5 illustrates the relationship between the events and state transition of each event. Tables 5.5,5.6 and 5.7 describe the parameters, states, and events used in this event graph.

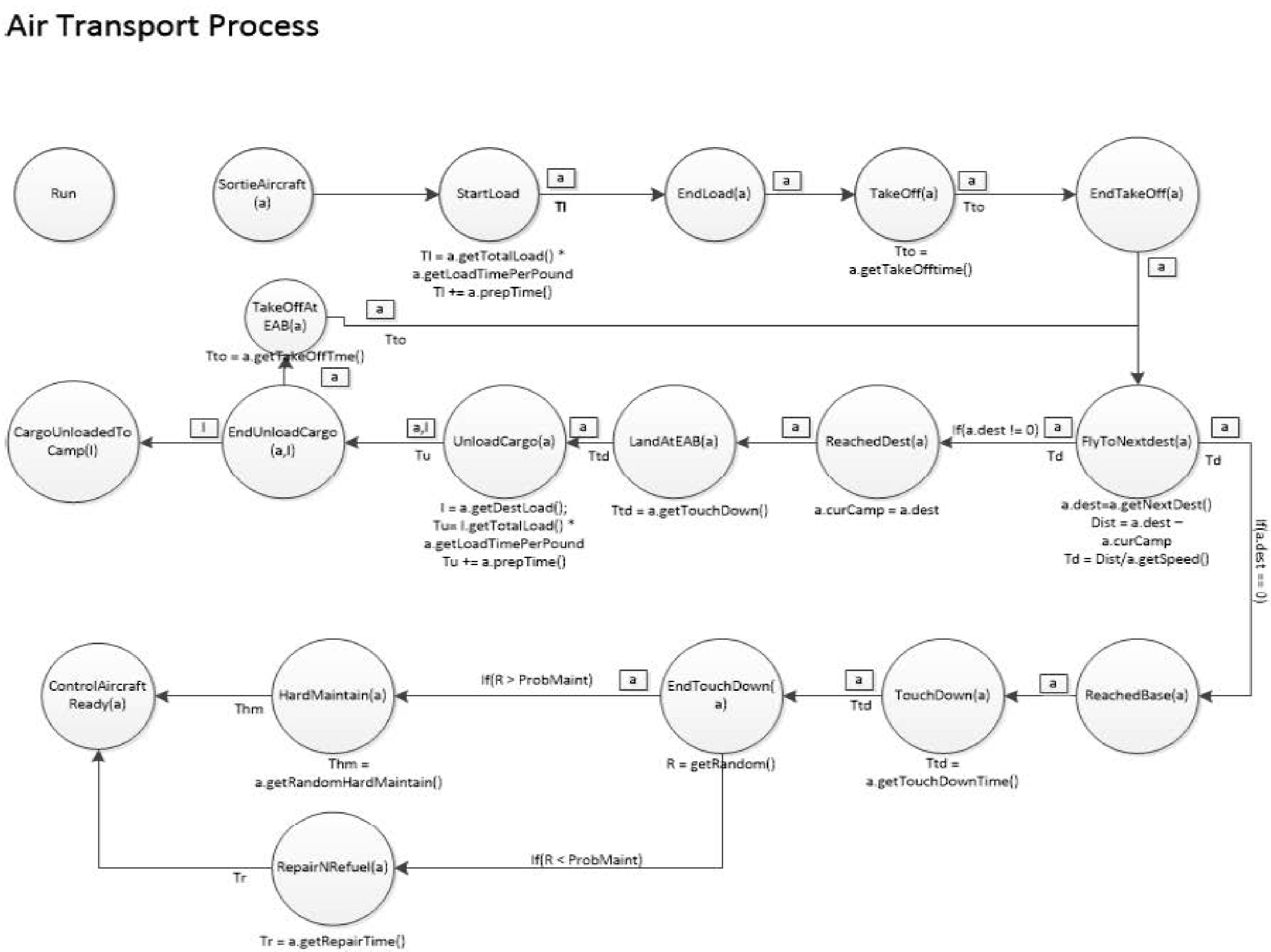

Figure 5.5: Air Transport Event Graph

Parameters

Table 5.5 describes the parameters used for the `Air Transport Process`. The parameters are used to instantiate or calculate the time and probability.

Parameters	Variable	Description
Tl	double	Time to load the cargo onto the aircraft
Tto	double	Time to take off (Mins)
Td	double	Time to next destination (Mins)
Tu	double	Time to unload the cargo to EAB (Mins)
Ttd	double	Time to touch down (Mins)
Thm	double	Time to hard maintain the aircraft (Mins)
Tr	double	Time to repair and refuel the aircraft for next mission (Mins)
ProbMaint	double	Probability of maintenance

Table 5.5: Parameters of the Air Transport Process

States

Table 5.6 describes the states that are affected by the Air Transport Process.

States	Variable	Description
l	CargoLoad	Cargo Load delivered by aircraft
a	Aircraft Entity	The aircraft entity stores some states that are changed in this process • curCamp : Stores the current camp id • dest : Stores the next destination id that the aircraft will visit • loadMap : The map that stores the cargo information that was delivered to the designated camps
R	double	Probability of Maintenance

Table 5.6: States of the Air Transport Process Event Graph

Events

Table 5.7 shows the events used in the event graph

Events	Objects	Description
Run		Initialize the process for each run of simulation
SortieAircraft(a)	Input:Aircraft (a) Output:Aircraft (a)	Command Sent from the Air Command to start loading cargo and deliver to the destination
StartLoad	NA	Start Loading the cargo into the aircraft • `TimeToLoad (Tl) = total load` × `loadTime per pound + preparation time` • Preparation time means the time to prepare the aircraft for flight.
EndLoad(a)	Input:Aircraft (a)	Finished Loading the cargo onto the aircraft and signify the aircraft is ready for flight
TakeOff(a)	Input:Aircraft (a) Output:Aircraft (a)	Start to take off from the airport • Time to take off (Tto) is predefined during initialization
FlytoNextDest(a)	Input:Aircraft (a) Output:Aircraft (a)	Decide the next destination to fly to • Retrieve the first destination from the `a.loadMap`. `a.dest = a.getNextDest()` • Retrieve the distance to next destination. `dist = getDistance(a.dest - a.curCamp)` • Calculate the time taken to reach the next Destination by dividing distance by speed. `Td = dist/a.getSpeed()` • if loadMap is empty, it means all cargo has been delivered. Return to base.

Events	Objects	Description
ReachedDest(a)	Input:Aircraft (a) Output:Aircraft (a)	Aircraft has reached the destination • Set the destination as the current camp
TouchDownDest(a)	Input:Aircraft (a) Output:Aircraft (a)	Land aircraft at Destination Optional (Some Aircraft unsling their load and need not touch down) Ttd is 0 when not landing Time to touch down (Ttd) is predefined
UnloadCargo(a)	Input:Aircraft (a) Output:Aircraft (a)	Start to unload the cargo at the destination • Get the designated Load from loadMap • Calculate the time to unload the cargo. `Tu = total load` $\times$ `loading time per pound` • Include time for the aircraft to be ready for flight `Tu += preparation time`
EndUnloadCargo(a)	Input:Aircraft (a) Output:Aircraft (a) Output:CargoLoad (l)	Finished unloading the cargo at the destination • Get the cargo information from loadmap. `i = loadMap[curCamp]` • Remove the cargo information from loadmap
CargoUnloaded ToCamp (l)	Input:CargoLoad (l)	Inform EAB that a consignment of cargo has been delivered • Remove the cargo information from loadmap
ReachedBase(a)	Input:aircraft (a) Output:Aircraft (a)	Aircraft has reached the skyline of the base camp. Prepare to land
TouchDown(a)	Input:aircraft (a) Output:Aircraft (a)	Start to Land at base camp • Time to land (Ttd) is predefined
EndTouchDown(a)	Input:aircraft (a)	Landed the aircraft at base camp

Events	Objects	Description
	Output:Aircraft (a)	• Get Random number (R) to decide next action • If `R > Probability of hard maintain`, it is time to maintain the aircraft • If `R < Probability of hard maintain`, Refuel and perform minor repairs to prepare the aircraft for flight
ControlAircraft BaseReady(a)	Input:aircraft (a)	Report to air command that aircraft is ready for next mission

Table 5.7: Events of the Air Transport Process Event Graph

5.2.3 Base Camp Process Event Graph

The `Base Camp Process` first instantiates the variables. The model uses a priority queue to prioritize the orders according to the mode of urgency. This means the orders with the highest urgency were prepared first.

The `Base Camp Process` Event graph is responsible for modeling the stages of the logistics center and the airport. Requests arrive in the queue and are inserted into the request queue (`reqQ`) and sorted according to its urgency. The model assumes that there are multiple warehouses in the logistics center. Each warehouse retrieves the orders from the top level of the request queue and processes the orders.

The model then places the orders into the processing queue (`processingQ`) to keep track of the orders being processed. Once the warehouse finished preparing the load, the team removes the orders from the processing queue and inserts it into the ready Qqueue (`readyQ`) to signify the loads are ready for delivery to the airport. The delivery team takes over and delivers the cargo to the airport.

The air command looks into its aircraft queue to determine the availability of its aircraft fleet before designating the aircraft to deliver the goods. Every aircraft ready for delivery is inserted into the aircraft queue (`aircraftQ`). Once the air command has designated the aircraft to deliver, it sends an `AircraftSortie` Event to the aircraft to the Air Transport Process Model to start loading the goods and transport the goods to the designated EABs.

Figure 5.6 illustrates the relationship between the events and state transition of each event. Tables 5.8, 5.9 and 5.10 describe the parameters, states, and events used in this event graph.

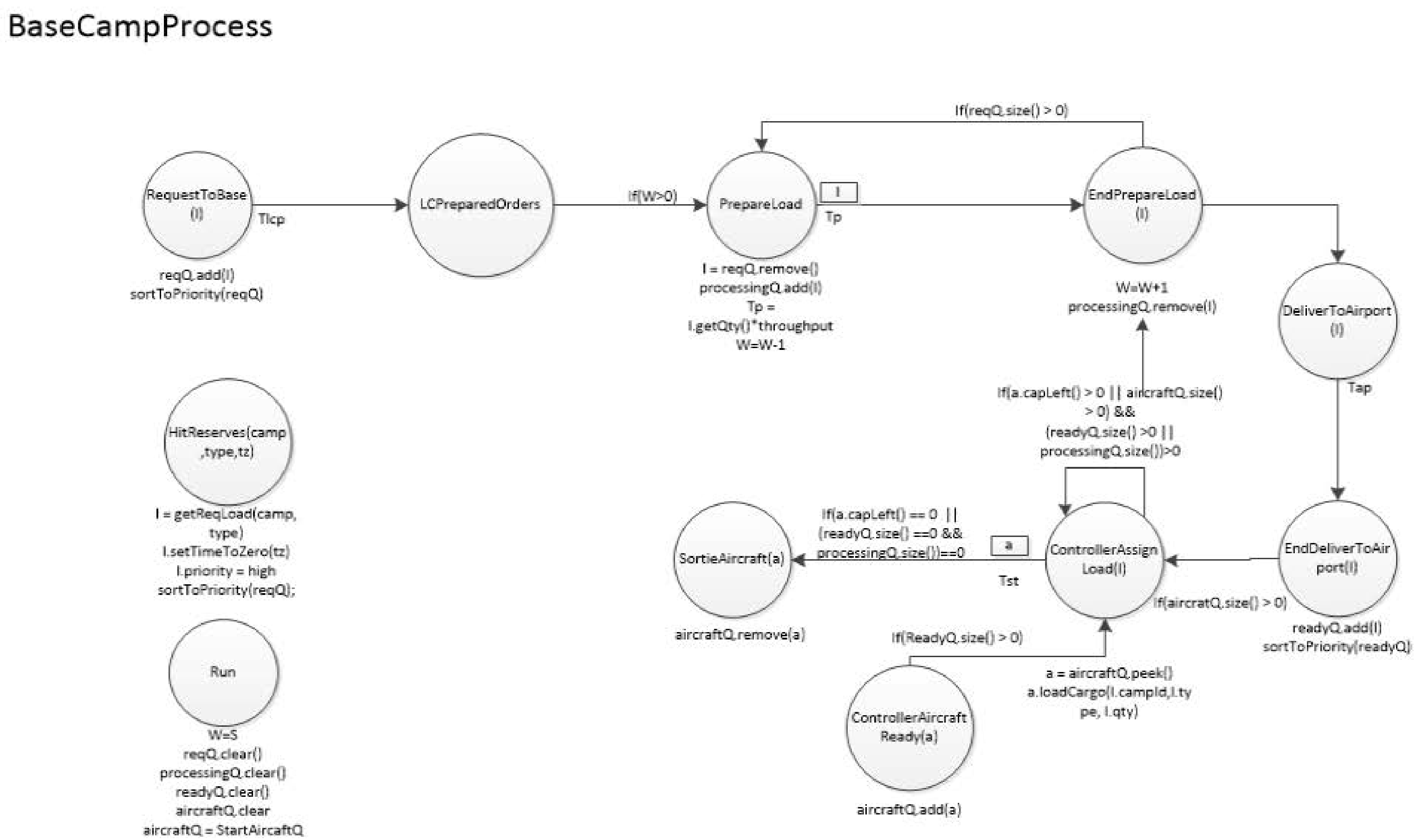

Figure 5.6: Base Camp Process Event Graph

Parameters

Table 5.8 describes the parameters used for the `Base Camp Process` Event Graph. The parameters are used to instantiate the number of teams available and the time and throughput to prepare the cargo. `CampList` stores the camps available in this simulation for information purposes.

Parameters	Variable	Description
S	int	Maximum number of teams available to prepare the cargo for delivery
Tlcp	double	Time for the logistics center to process each request (Mins)
Tp	double	Time for each team to prepare the orders in the warehouse (Mins)
Tap	double	Time to deliver the cargo from the warehouse to the airport (Mins)
Tst	double	Time for the air command to decide the aircraft to deliver the cargo (Mins)
throughput	double	The throughput of the each team preparing the cargo for delivery (lbs./min)
campList	ArrayList<Camp>	The list of camps available in this simulation
startAircraftQueue	ArrayList<Aircraft>	Start state of aircraft available - For initialization in every run

Table 5.8: Parameters of the Base Camp Process

States

Table 5.9 describes the states used for the `Base Camp Process`.

states	Variable	Description
W	int	Number of teams available to prepare the cargo for delivery
campList	ArrayList<Camp>	List of Camps available for the simulation - To store the details of camps

states	Variable	Description
aircraftQueue	ArrayList<Aircraft>	List of aircraft available for delivery of cargo to EABs
requestQueue	PriorityQueue <Request>	List of cargo requests from EABs
readyReqQueue	PriorityQueue <Request>	List of cargo ready to be delivered to the EABs
processingQueue	PriorityQueue <Request>	List of requests currently under processing

Table 5.9: States of the Base Camp Process Event Graph

Events

Table 5.10 shows the events used in the `Base Camp Process` event graph. In the table, l refers to the CargoLoad Entity object and a refers to the Aircraft Entity object.

Events	Objects	Description
Run		Initialize the process for each run of simulation
RequestToBase(l)	Input:CargoLoad (l) Output:CargoLoad (l)	Load Requested by the EAB
LCProcessOrder(l)	Input:CargoLoad (l)	Load Requested by the EAB • Add requested load into the request queue • Sort the request queue according to the highest priority
PrepareLoad	NA Output:CargoLoad (l)	Warehouse prepares the cargo for delivery • Remove the request from the top of the request queue • Insert the order into the processing queue • Calculate the time to prepare the orders

Events	Objects	Description
		• Decrement the number of teams available for preparing goods.
EndPrepareLoad(l)	Input:CargoLoad (l) Output:CargoLoad (l)	Warehouse finished preparing the cargo • Remove the finished order from the processing queue • Increment the number of teams available for preparing goods
DeliverTo Airport(l))	Input:CargoLoad (l) Output:CargoLoad (l)	Deliver the finished orders to the airport
EndDeliverTo Airport(l)	Input:CargoLoad (l)	Finished delivering the cargo to airport • Insert the delivered order into the ready queue
ControllerAssign Load(l)	Input:CargoLoad (l) Output:Aircraft (a)	Finished delivering the cargo to airport • If aircraft is fully loaded, order the aircraft to sortie • If aircraft is not fully loaded and it is not loaded with priority orders, wait for the aircraft to be fully loaded before sortie. • If aircraft is loaded with priority orders, and other priority orders are currently being processed, wait for the aircraft to be fully loaded before sortie. • If aircraft is loaded with priority orders, and no priority orders are under process, the commands sends the sortie command immediately.

Events	Objects	Description
AircraftSortie(a)	Input:Aircraft (a)	Order the aircraft to load cargo and sortie. This process is listened by the Air Transport Process • Remove aircraft from aircraft queue
HitReserves(l)	Input:campId, type and time to zero (tz)	EAB has hit reserves and request the orders to be upgraded to higher priority • Set the orders in the request queue to be high priority
ControllerAircraft Ready(a)	Input:aircraft (a)	A message from aircraft that the aircraft is ready for delivery • Insert the aircraft to aircraft queue

Table 5.10: Events of the Base Camp Process Event Graph

5.2.4 Consumption Process Event Graph

The `Consumption Process` first instantiates the variables . The model follows a conveyor belt pattern, whereby after processing an event, the entities are passed on to the next event for processing.

The `Consumption Process` event graph is responsible for modeling the consumption behavior of an EAB. Each type of consumable has a consumption rate. Once it reaches the trigger limits, it sends a request to the base camp. At the same time, it queues an event to trigger the `hitReserves` event that notifies the base camp to upgrade the order to a high priority order, when the supply limit hit the reserves. However, if the load is replenished on time, a canceling edge is triggered to cancel the `hitReserves` event in the event graph, i.e., the `hitReserves` event is no longer triggered.

Figure 5.7 illustrates the relationships between the events and state transitions. Table 5.11, 5.12 and 5.13 describe the parameters, states, and events used in this event graph.

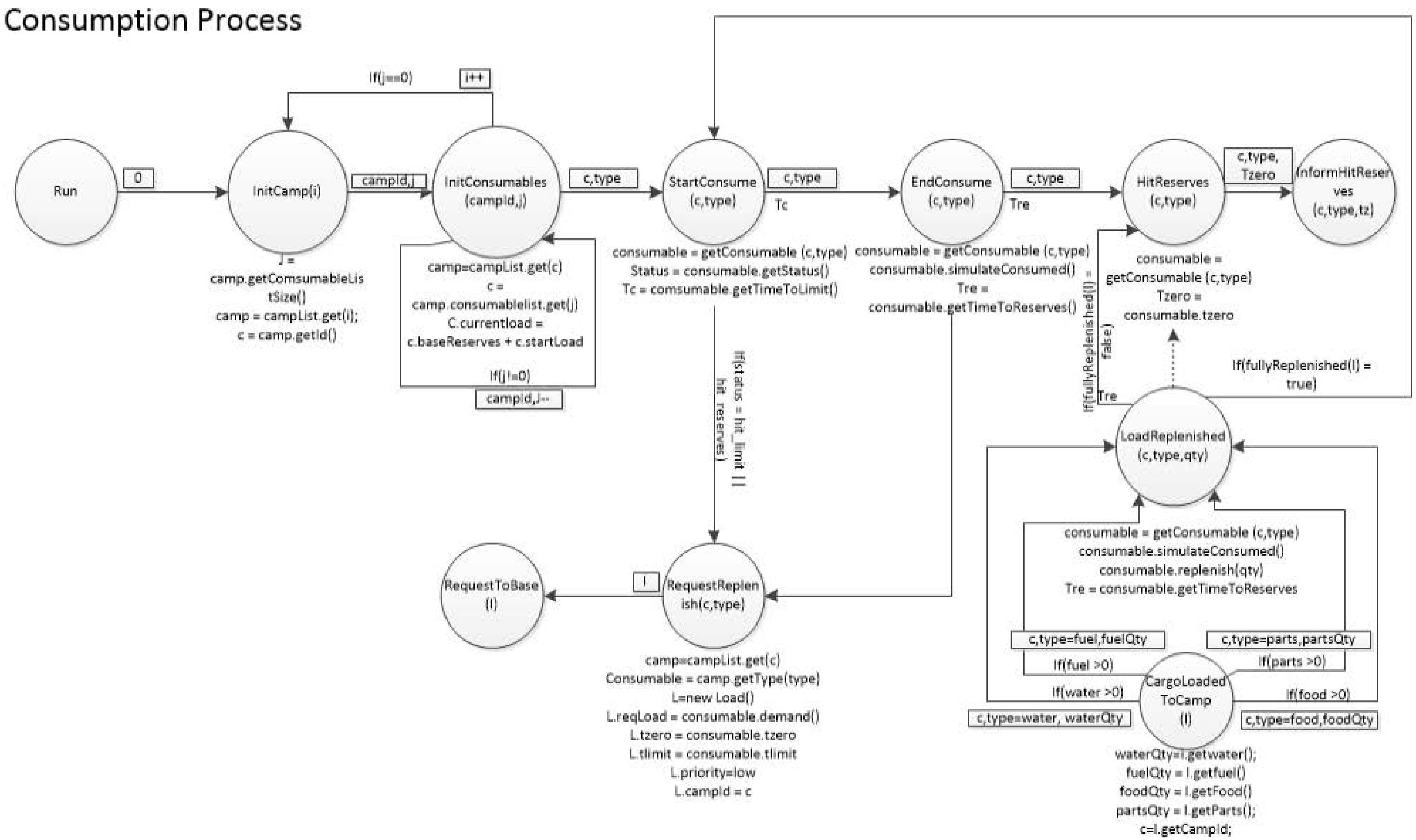

Figure 5.7: Consumption Process Event Graph

Parameters
Table 5.11 describes the parameters used for the Consumption Process. The parameters are used to instantiate the list of consumables for each camp. The `campList` stores the camps available in this simulation for information purposes.

Parameters	Variable	Description
Tc	double	Time to consume the consumables until it reaches trigger limits for requests (Mins)
Tre	double	Time for consumables to hit the reserve limits (Mins)
limits	double	The level of consumables available before triggering the requests for resupply. (lbs.)
campList	ArrayList<Camp>	The list of camps available in this simulation

Table 5.11: Parameters of the Consumption Process Event Graph

States
Table 5.12 shows the states used in the event graph

State	Variable	Description
consumable	ConsumablesEntity (c)	The current quantity of consumables State Changed : c.currentLoad

Table 5.12: Parameters of the Consumption Process Event Graph

Events

Table 5.13 shows the events used in the event graph used in the Consumption Process.

Events	Objects	Description
Run		Initialize the process for each run of simulation
InitCamp(i)	Input:Index (i) Output:campId(campId) and index (j)	Retrieve the consumable information from each camp
InitConsumables(j)	Input:campId (campId) and Index (j) Output:consumables entity (c) and consumable type (type)	• Initialize the consumables current load to default state • Retrieve the consumable information from consumables entity to start the consumption process
StartConsume (c,type)	Input:Consumables Entity (c) and type Output:consumables entity (c) and consumable type (type)	Consume at a constant rate • Get Time to hit the replenish limit. (Tc)
EndConsume (c,type)	Input:Consumables Entity (c) and type Output:consumables entity (c) and consumable type (type)	Reaches the limit to replenish • Get Time to hit the reserves limits. (Tre)
RequestReplenish (c,type)	Input:Consumables Entity (c) and type Output:Cargoload (l)	Pack the requests into an order form Set the information of time to zero, time to hit reserves limit, the demands and campId into CargoLoad. The order form are sent to the base camp for processing

Events	Objects	Description
RequestToBase (l)	Input:Cargoload (l)	Forward the order form to base camp for processing
HitReserves (c,type)	Input:Consumables Entity (c) and type Output:consumables entity (c) and consumable type (type) and Tzero	Hit the reserves limit • Get Time to hit the zero cargo limit. (Tzero)
InformHitReserves (c,type)	Input:Consumables Entity (c) and type Output:consumables entity (c) and consumable type (type)	Inform the base camp that the EAB has hit the reserves limit. Request to upgrade order to high priority
CargoLoadedToCamp (c,type)	Input:Cargoload (l) Output:consumables entity (c) and consumable type (type)	Cargo has been delivered by the aircraft to the EAB. • Separate the goods delivered into different categories
LoadReplenished (c,type,qty)	Input:Consumables Entity (c), type and quantity Output:consumables entity (c) and consumable type (type)	Replenish the stocks of consumables. • Send Canceling edge to hit reserves • Recalculate the time to hit reserves and send another event to update the time to hit reserves. • If the load requests are fulfilled, repeat the consumption process. There is no need to send a hitReserves event after the requests are fulfilled.

Table 5.13: Events of the Consumption Process Event Graph

5.2.5 High-Level Event Graph

The high-level event graph shows the source-to-listener relationships between the models and the connectivity of the models. The arrow defines the direction of the information flow. Figure 5.8 illustrates a high level event graph.

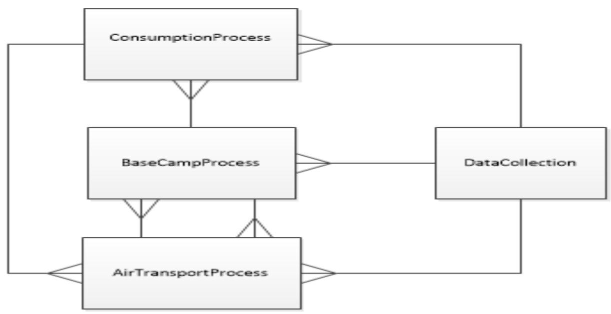

Figure 5.8: High Level Event Graph. This figure shows a high level event graph. The arrow bar is connected to the source model, and it defines the direction of the information flow. For example, the ConsumptionProcess is the source and its listener is the BaseCampProcess

The discrete event simulation works on a source-to-listener relationship. A model could be implemented to listen to events from other sources. Events common in the source and listener models will be executed together at the same time.

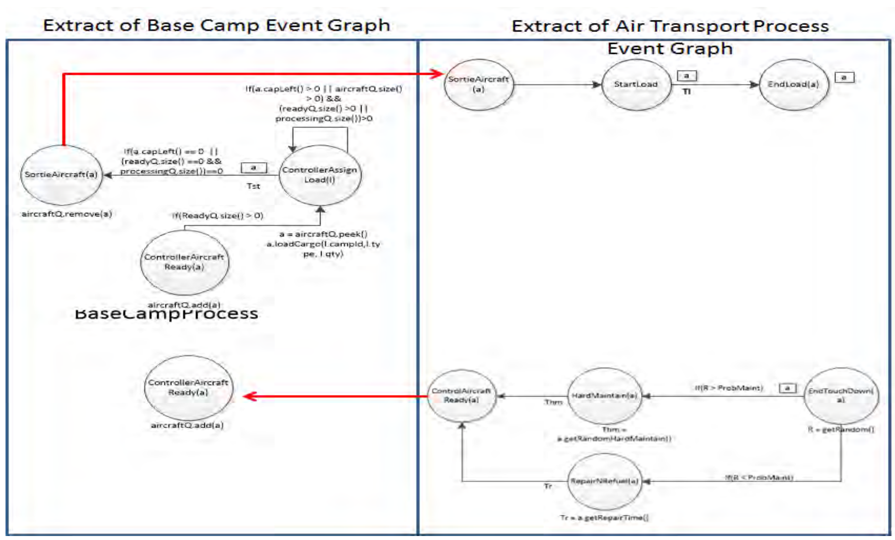

Figure 5.9: Example of the Event Listener. This figure shows an extraction of the Air Transport Process and the Base Camp Process. In this figure, the Air Transport Process is listening to the `SortieAircraft` event queued by the Base Camp Model, whereas the Base Camp is listening to the `ControllerAircraftReady` event queued by the Air Transport Process.

For example, the `Base Camp Process` completed packing the supplies and has assigned an aircraft to deliver the supplies. A `sortieAircraft` event is queued for processing. The `Air Transport Process` listens to the queue. Thus, when the `SortieAircraft` event is executed, both the `Base Camp Process` and the `Air Transport Process` processes the events at the same time. Figure 5.8 illustrates an example of the interconnectivity between the `Air Transport Process` and the `Base Camp Process`.

The same is applied to the `ControllerAircraftReady` event. When the aircraft has been refueled or maintained, it reports its availability to the base camp. A `ControllerAircraftReady` event is queued by the `Air Transport Process`. When the event is executed, the `Base Camp Process` is informed of the availability and adds the aircraft into its aircraft queue. Thus, these examples show the connectivity of the models and their linkages. Table 5.14 shows the remote events listened by each model.

	Listener	**Events Listened**	**Source**
1	Air Transport Process	SortieAircraft	Base Camp Process
2	Base Camp Process	ControlAircraftReady	Air Transport Process
		RequestToBase	Consumption Process
		HitReserves	Consumption Process
3	Consumption Process	CargoLoaded	Air Transport Process
4	Data Collection Process	SortieAircraft	Base Camp Process
		ControlAircraftReady	Air Transport Process
		RequestToBase	Consumption Process
		HitReserves	Consumption Process
		CargoLoaded	Air Transport Process

Table 5.14: This table shows the source and listener link, and the events listened by each model.

To assist in the data analysis, a `Data Collection model` is developed. The model acts as a shell to listen to the events, listed in Table 5.14, and extracts the performance data for analysis purposes. The performance data extracted are described together with the experimentation setup, in Section 6.2.

5.2.6 Discrete Event Simulation Software

Software, including source code, and associated documentation can be found at "http: // faculty.nps.edu/thchung" under "Resources, Software."

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CHAPTER 6:
Simulation Experiments and Analysis

6.1 Experiment Setup

6.1.1 Aim of the Experiments

Experiments were set up with the aim of finding the optimal fleet size and mix to support the logistical supplies of the EABs. In addition, a sensitivity analysis was performed to determine the amount of supplies required to sustain the EABs. The following sections provide the details on the data used, the experimental setup, and the results and analysis.

6.1.2 Scenario Overview

The scenario leveraged the South China Sea scenario used by SEA-20B to explore the effectiveness of the DAW solution. SEA-20B recommended that ten EABs be setup in Vietnam and Philippines to provide full defensive coverage in the South China Sea to prevent adversaries from encroaching on the Spratly Islands. This thesis adds on to the scenario by recommending that the Cam Ranh Bay and Subic Bay serve as the MOBs for Vietnam and Philippines, respectively. Figure 6.1 shows the proposed locations of the MOBs and EABs.

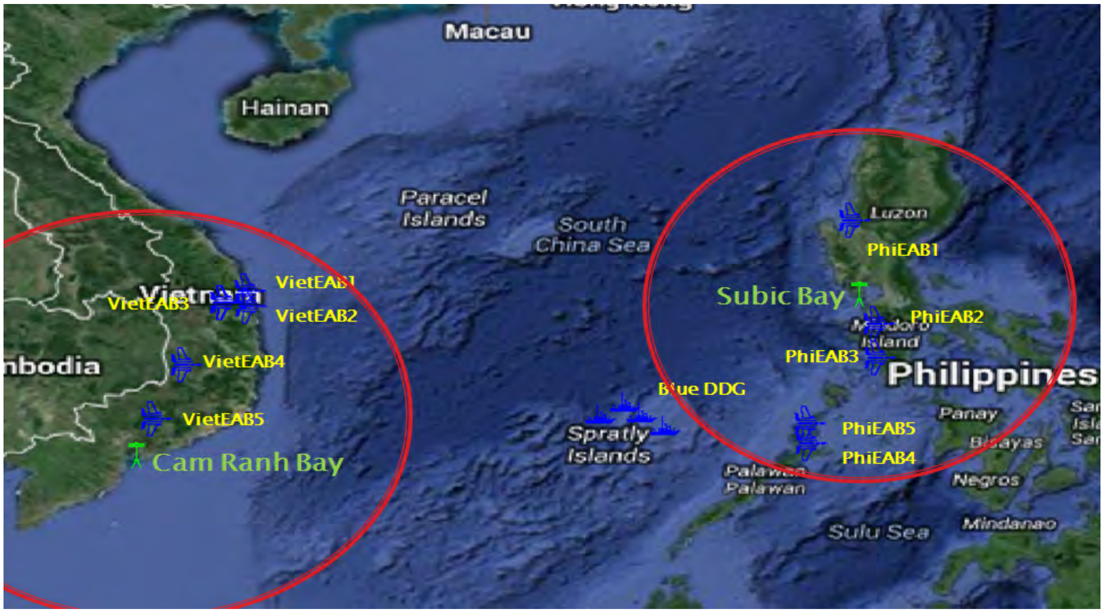


Figure 6.1: Proposed Locations of the Main Operating Bases and Expeditionary Air Bases. There are ten EABs, five in Philippines and five in Vietnam, set up to provide full coverage of the South China Sea. The logistics supply of the EABs is be served by the logistics center in the Cam Ranh Bay and Subic Bay. The red circle shows the maximum distance and area that each logistics center could support.

6.1.3 Data Used for the Experiments

The data used for the simulations are extracted from open sources, such as the call for papers from DOD and DARPA [22], [44], research papers [18], [45], news articles [19], [46], manufacturers' specifications [31], [47], and best estimates based on comparison with similar UAVs. The data sources might not be accurate since most of the UAV platforms are currently under development. The experiments aim to generate valuable insights to determine the possibility of using the platforms for transporting cargo in the future. Future studies could be conducted using accurate data, when the platforms are developed, to validate the feasibility of the solutions. The collated characteristics of the cargo aircraft and the data used in the presented model are shown in Table 6.1 and Table 6.2. Stochastic elements, such as the maintenance time, consumption rate, and preparation times, were inserted to simulate the delays and uncertainties faced in real life scenario.

Table 6.1 shows the summary of the parameters used in the simulation model. Refer to Chapter 5 for the detailed description of the model development, and the parameters used in each Event Graph.

Parameters/ type	**Units**	**Fixed Wing**	**Rotary Wing**	**Airship**	**Trucks**
Acquisition Cost	USD (Millions)	25.0	5.0	40.0	0.35
Cost Per Hour	USD	3,000	1,200	1,500	100
Avg. Speed	Miles per hour	345	92	140	17.5
Max. Capacity	lbs.	10,000	6,000	132,000	20,000
Max. Distance	Miles	2,300	1,150	1,930	infinite
Time To Refuel	Mins	10	10	60	10
Time To Maintain	Mins	120	120	240	120
Time To take Off	Mins	5	5	0	0
Time To Land	Mins	5	5	0	0
Loading Time	Mins	30	30	30	30

Table 6.1: Vehicles Parameters Used for the Simulation Model

Table 6.2 shows the vehicle parameters used in the optimization model. The parameters used are the same as those of the simulation models. Refer to Chapter 4 for the detailed description of the models parameters, and equations used in the optimization model.

Parameters/ type	Units	Fixed Wing	Rotary Wing	Airship	Trucks
$speed_k$	Miles per hour	10,000	6,000	132,000	20,000
cap_k	lbs.	10,000	6,000	132,000	20,000
$costHour_k$	USD	3,000	1,200	1,500	100
$costAC_k$	USD (Millions)	25.0	5.0	40.0	0.35
$loadPrepTime$	Mins/lbs..	0.001	0.001	0.001	0.001
$refuel_k$	Mins	10	10	60	10
$tripPrepTime$	Mins	5	5	5	5
$MaxLogTime$	Mins	4320	4320	4320	4320
M_{Qty}, M	Mins	200,000	200,000	200,000	200,000

Table 6.2: Vehicles Parameters used for the Optimization Model

The distance from base to base for aircraft movement is assumed to be of Euclidean distance as shown in Tables 6.3 and 6.4. As trucks have to traverse between the undulating terrains or fixed paved roads, it is assumed that they will travel twice the distance of an aircraft. In order to use a fixed set of distance table for all experiments, it is assumed that the speed of each aircraft is halved, from 35 miles per hour to 17.5 miles per hour, to simulate the longer distance traveled.

	Cam Ranh	Viet1	Viet2	Viet3	Viet4	Viet5
Cam Ranh	0	450	376	403	371	88
Viet1	450	0	88	98	139	415
Viet2	376	88	0	44	62	333
Viet3	403	98	44	0	44	353
Viet4	371	139	62	44	0	316
Viet5	88	415	333	353	316	0

Table 6.3: Euclidean Distance between the Camps in Vietnam (in Miles)

	Subic	Phi1	Phi2	Phi3	Phi4	Phi5
Subic	0	139	139	223	361	403
Phi1	139	0	277	350	483	527
Phi2	139	277	0	124	255	294
Phi3	223	350	124	0	139	181
Phi4	361	483	255	139	0	44
Phi5	403	527	294	181	44	0

Table 6.4: Euclidean Distance between the Camps in Philippines (in Miles)

6.2 Key Measures

6.2.1 Performance Requirements

Using the criteria from MALSP II, this thesis translates the goals into key requirements for the development of the models. The turnaround time between the request and delivery of goods between MOB and EAB should be less than three days. Sufficient goods should be available within the EAB and the quantity of goods should not fall below zero level. Finally, the cost of operations should be minimized.

6.2.2 Measures of Effectiveness

In 2010, the Naval Logistics outlined four goals in the logistics strategic plans to improve their operations. The aims of the plans are to improve the logistics responsiveness and agility, reduce workload both afloat and ashore, improve combat support readiness, and recapitalizes funding of naval logistics for more efficient use of resources [48]. Together with the key requirements, the Measures of Effectiveness (MOE) are developed to compare the effectiveness of each platform. Table 6.5 shows the MOEs developed. Table 6.6 shows the performance data that are recorded during the simulation runs.

No.	MOE (Per Vehicle)	Units	Description
1	Load per Travel Time	lbs. / min	This parameter measures the load carried per minute for each vehicle. • Load Per Travel Time = Average Load Per Trip / Average travel time per Trip
2	Load per distance	lbs./ mile	This parameter measures the load carried per distance traveled for each vehicle.
3	Cost of Operations	USD	This parameter measures the cost of operations incurred for a year of operations. • Cost of operations = Total cost of Acquisition + Total cost of Traveling. • Total Cost of Traveling = Total Traveling Hours * Cost of Travel per hour
4	Manpower required	-	Number of pilots required to perform the missions for a year of operations.

Table 6.5: Description of the Measures of Effectiveness

Aircraft			
No.	**Performance Measure**	**Units**	**Descriptions**
1	Total Platforms	-	Number of vehicles used to support the logistics operations
2	Avg. no. of trips per vehicle	-	Average number of trips performed by each vehicle each year
3	Avg. Distance per trip per vehicle	Miles	Average distance traveled per trip
4	Avg. Load per trip per vehicle	lbs.	Average capacity utilized per trip
5	Avg. Travel Time per vehicle	Mins	Average time taken to complete each trip
6	Avg. MaintTime per vehicle	Mins	Average maintenance time before each trip
7	Avg. Unused Time per vehicle	Mins	Average time unutilized before each trip
EAB			
No.	**Performance Measure**	**Units**	**Descriptions**
1	Avg. Turnaround time	Mins	The average time for each order to be fulfilled. Turnaround time = Time when loads are fully delivered - Time when EAB requested for goods
2	Avg. Load per Request	lbs.	The amount of consumable requested per order
3	Avg. Trips to Refill	-	The average number of deliveries before each requests are fulfilled

Table 6.6: Description of the Performance Measures

6.3 Experiment 1: Tuning the Vehicle Routing Optimization Model

The Vehicle Routing Problem (VRP) Optimization model (see Chapter4 for the design of optimization model) was used to find the optimal fleet size and mix to support the logistical needs of the EABs. An optimization model does not account for the stochastic real-world behavior. Thus, a Discrete Event Simulation Model (DES) is developed to model the stochastic behaviors of the supplies and used to test the feasibility of the optimization model. Tuning was done to the supplies preparation time and maximum trips allowable to compensate for the lack of realistic stochastic behavior. The feasibility test is done by ensuring the EAB's requests are fully fulfilled within three days after requesting for supplies, as stipulated in MALSP II.

6.3.1 Operating Theater

In this experiment, this thesis uses Vietnam as the operating theater. The experiment splits the demands of Vietnam into two categories. Food, water, and parts form the non-toxic and non-flammable category. Fuel, which is flammable and require additional safeguards, could not be mixed with the other supplies. Hence, separate vehicles are dedicated to each category.

6.3.2 Simulation Experiments

The experiment starts with the running of the VRP model with a homogeneous vehicle profile. This means that the VRP model was injected with the data of a single vehicle type, with the aim of finding the optimal solution for each vehicle type. The VRP results are inserted into the DES model to test the feasibility of the recommended platform count. Thereafter, the VRP model is fine-tuned until it meets the demand requirements. This iterative process is carried out for every vehicle type to ensure the parameters used for the model are sound. After ensuring the parameters used are feasible, the VRP model is run with the heterogeneous vehicle profiles. This means that the VRP model is injected with the profiles of all vehicle types. The optimization model is run using GAMS to determine the optimal fleet size and mix.

In this scenario, each EAB carries a week of supplies and expects them to be replenished

within three days after requesting to the base camp. Each run of the DES simulates 52 weeks (524,160 minutes) of logistics operations within the Vietnam operating theater. A regression of 1,000 runs is performed for each vehicle type.

6.3.3 Results and Analysis

Table 6.7 shows the results of the recommended solutions before and after tuning.

Performance	Airship	Rotary Wing	Fixed Wing	Trucks	Mixed
Recommended by VRP -Food, Water, Parts	1	8	5	13	1 Airship
After tuning	1	6	2	14	1 Airship
Recommended by VRP -Fuel	-	-	-	-	3 Airships
After tuning	-	-	-	-	3 Airships

Table 6.7: Results of the Optimization model

As seen in Table 6.7, there are some discrepancies in the optimal results provided by VRP model against the DES model. The VRP model recommendations for the fixed wing and rotary wing UAVs are slightly greater than from the DES model, whereas the computed number of trucks is lower than the DES model results. Tuning is performed to compensate for the lack of realistic stochastic behavior. After tuning the models, a heterogeneous VRP model was run to determine the optimal fleet size and mix. Of particular note is that one airship is capable of meeting the demands of the food, water, and parts, and three air ships are required to meet the fuel demands of the EABs in Vietnam.

The next section analyzes the performance data of each vehicle type to determine the cost-effectiveness of each vehicle type.

6.4 Experiment 2: Comparison of the Vehicle Types

The scenario setup and the simulation runs are the same as Experiment 1. In this experiment, the performances of each vehicle types are recorded. . Section 6.4.1 shows the data recorded from the experiment. Sections 6.4.2, 6.4.3 6.4.4, provide detailed analysis of the load efficiency, travel time, and costs of each vehicle type. From this analysis, the cost-effectiveness of each vehicle type could be determined.

6.4.1 Data Generated from the Experiment

Table 6.8 and 6.9 shows the data generated from the experiments. The table records the performance measures as described in section 6.2.2. The data shows the mean values and the standard deviation generated from the regression runs.

No.	Performance	Units	Airship	Rotary Wing	Fixed Wing	Trucks
1	Total Platforms	-	1	6	2	14
2	Avg. No. of Trips per vehicle	-	792.11 ± 1.17	1496.44 ± 1.54	2793.52 ± 4.37	221.95 ± 0.28
3	Avg. Distance per Trip per vehicle	Miles	456.91 ± 0.23	366.59 ± 0.20	360.79 ± 0.22	498.94 ± 0.42
4	Avg. Load per Trip per Vehicle	lbs.	65704.33 ± 89.79	5813.97 ± 0.41	9351.93 ± 1.12	17650.54 ± 8.51
5	Avg. Travel Time per Vehicle	Mins	291.52 ± 0.11	274.89 ± 0.13	111.45 ± 0.04	1830.82 ± 1.40
6	Avg. MaintTime per Vehicle	Mins	77.87 ± 0.12	21.00 ± 0.02	32.99 ± 0.06	155.97 ± 0.12
7	Avg. Unused Time per Vehicle	Mins	293.81 ± 0.98	55.65 ± 0.26	43.83 ± 0.27	388.05 ± 1.78

Table 6.8: Performances Results of the Transport Vehicles

Performance	Airship	Rotary Wing	Fixed Wing	Trucks
Food				
Avg. Turn Around Time	609.49 ± 3.20	2814.15 ± 37.47	1768.54 ± 15.15	3259.73 ± 70.75
Avg. Load per Request	1858.67 ± 0.56	1885.35 ± 3.45	1857.91 ± 0.86	1956.96 ± 8.09
Avg. Trips to Refill	1.01 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
Water				
Avg. Turn Around Time	1088.40 ± 2.70	3927.67 ± 30.16	3034.54 ± 12.13	3889.08 ± 67.51
Avg. Load per Request	259568.26 ± 73.30	258530.06 ± 200.73	257992.98 ± 68.50	263701.00 ± 616.78
Avg. Trips to Refill	2.07 ± 0.00	44.70 ± 0.15	26.60 ± 0.04	22.13 ± 0.11
Parts				
Avg. Turn Around Time	615.06 ± 3.14	2841.51 ± 41.86	1777.27 ± 15.42	3218.26 ± 68.05
Avg. Load per Request	4647.71 ± 1.39	4718.78 ± 10.50	4643.98 ± 2.23	4879.58 ± 19.12
Avg. Trips to Refill	1.01 ± 0.00	1.03 ± 0.00	1.00 ± 0.00	1.03 ± 0.00
Fuel				
Avg. Turn Around Time	2986.18 ± 11.30	-	-	-
Avg. load per request	1737523.93 ± 465.39	-	-	-
Avg. Trips to Refill	14.31 ± 0.02	-	-	-

Table 6.9: Effects of the Transport Vehicles Performances on the EABs

6.4.2 Analysis of the Vehicle Load Capabilities

The vehicle load capability per vehicle is defined as the amount of load that each vehicle could carry while traveling. The following analysis takes two measures for comparison; (1) The load carried by the vehicle per mile traveled, and (2) the load carried by the vehicle per minute traveled. Figure 6.2 illustrates the amount of load that each vehicle could carry for each trip. The more load carried by a platform in each trip translates to fewer trips required to resupply the EABs. In other words, this means the platform is operating at a higher utilization.

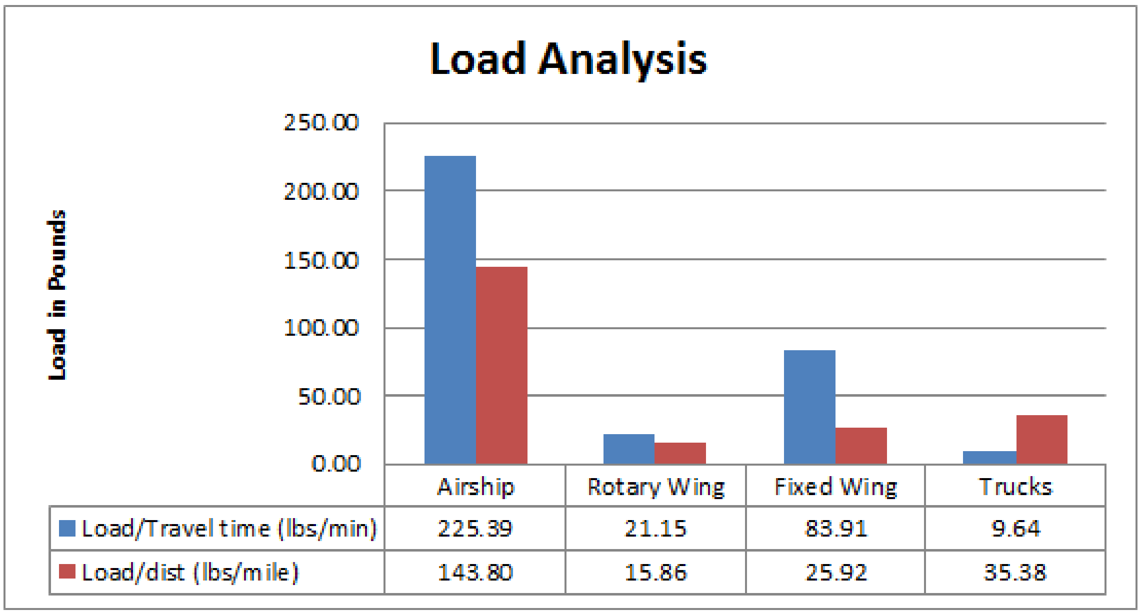


Figure 6.2: Load Analysis of the Vehicles for Experiment 2

Comparing the cargo UAV performances to the performance of trucks, the UAVs are capable of delivering greater loads at a faster speed than trucks, about two times or more. This advantage means that if the requests are urgent and need to be delivered within a short time period, the UAVs could meet the demands by delivering the loads at a faster speed. Due to the low payload capacity of the fixed wing and rotary wing UAVs, the amount of load per mile traveled is much lower. This trade-off means that if the EABs are located much farther from the base camps, the two aircraft types could require more trips to deliver the cargo to the EABs than trucks. Due to its large payload capacity, the airship possesses the highest advantage in terms of distance and time This analysis implies that it has the highest

efficiency among the platforms selected. Having high efficiency does not imply that it has the most cost-effective solution. The following sections performs a cost-comparison to determine the cost-effectiveness of each platform to further aid in the employment decisions.

6.4.3 Analysis of the Travel Time

The travel time denotes the amount of time taken to complete the whole mission, which approximately translates to the amount of manpower required to operate the platforms to complete the missions. Figure 6.3 illustrates the total time taken for each vehicle type to complete a year's operation. Figure 6.4 illustrates the average time that each vehicle travels per day.

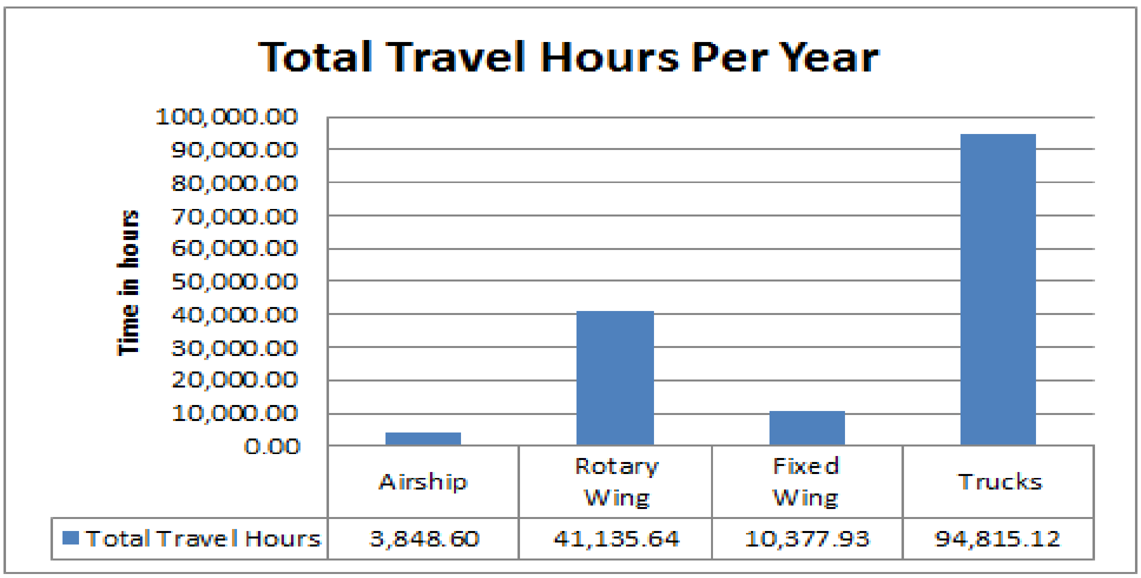


Figure 6.3: Travel Hours per Year by Vehicle Type. This figure shows the total travel hours needed by each vehicle type to support the logistics supply of EABs for a year.

The results show that the traditional means of using trucks take the most time to deliver all cargo required by the EABs for a year. This is due to the inherent low traveling speed and the extra time needed to traverse through roads and terrains. The UAVs took significantly less time to travel as they have a direct path in the skies and higher traveling speed.

The trucks and rotary wing UAV have the worst daily operating hours. Both vehicles need to operate about 19 hours a day to complete their missions. This places significant operator demands on the pilots or drivers operating these vehicles by having to operate long hours

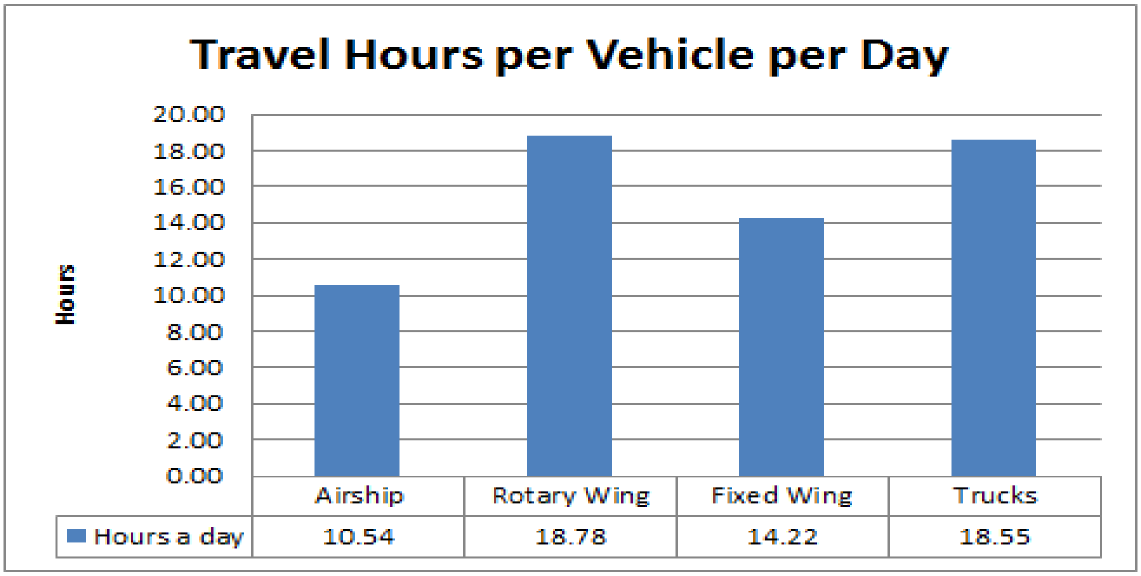


Figure 6.4: Travel Time per Day by Vehicle Type. This figure shows the average travel hours operated by each vehicle to support the logistics supply of EABs.

daily. Facing such long hours of work daily, fatigue is an issue and may increase the risks of accidents occurring. To prevent such mishaps from happening, suppose that each pilot or driver operate up to 12 hours a day, more operators are required to cater for sufficient rests between trips. Then, the number of manpower requirements for these 12-hours workday can be approximated as shown in Table 6.10.

	Airship	**Rotary Wing**	**Fixed Wing**	**Trucks**
Platforms Required	1	6	2	14
Operating Hours per Day	10.54	18.78	14.22	18.55
Personnel Required	1	12	4	28

Table 6.10: Manpower Required to Operate each Vehicle Type, in Terms of Operators assuming 12-hour Workdays

The manpower required for trucks is significantly more than the UAVs. According to the U.S. Air Force, one UAV operator could control up to three MQ-9 UAVs in 2012 [49]. In the DOD Unmanned Air Systems Integrated Road-map and the U.S. Air Force Unmanned Air Systems Flight Plan, [26], [49], they described their aim to eventually increase the UAV to operator ratio from the current 3:1 to 6:1, i.e., from three UAVs to one operator to six UAVs to one operator. If the vision is realized, the number of UAV operator required

to operate the cargo UAVs may drop even further. Due to the novelty of the cargo UAV technologies, this thesis made a conservative assumption to assign one operator to a UAV and eventually increase the ratio after the technology stabilizes. The analysis shows that the efficiency of UAVs can lead to a drop in the number of personnel needed to operate the vehicles daily. As trucks faces potential risks (e.g., IEDs along the path), the use of UAVs could help to circumvent the risks and accommodate greater conveniences.

6.4.4 Cost Analysis of the Vehicle Types

The total cost of operations consists of a fixed cost and a variable cost. The fixed cost is the total cost of acquiring the platforms to serve the operations, whereas the variable cost is dependent on the cost of operating the platforms, which is the traveling cost. In this analysis, this thesis uses the total cost to sustain the logistics supply for a year as means to compare the cost-effectiveness. Figures 6.3 and 6.5 show the total flight hours and total cost of operations to support the a year's operation of resupplying food, water, and parts to the EABs.

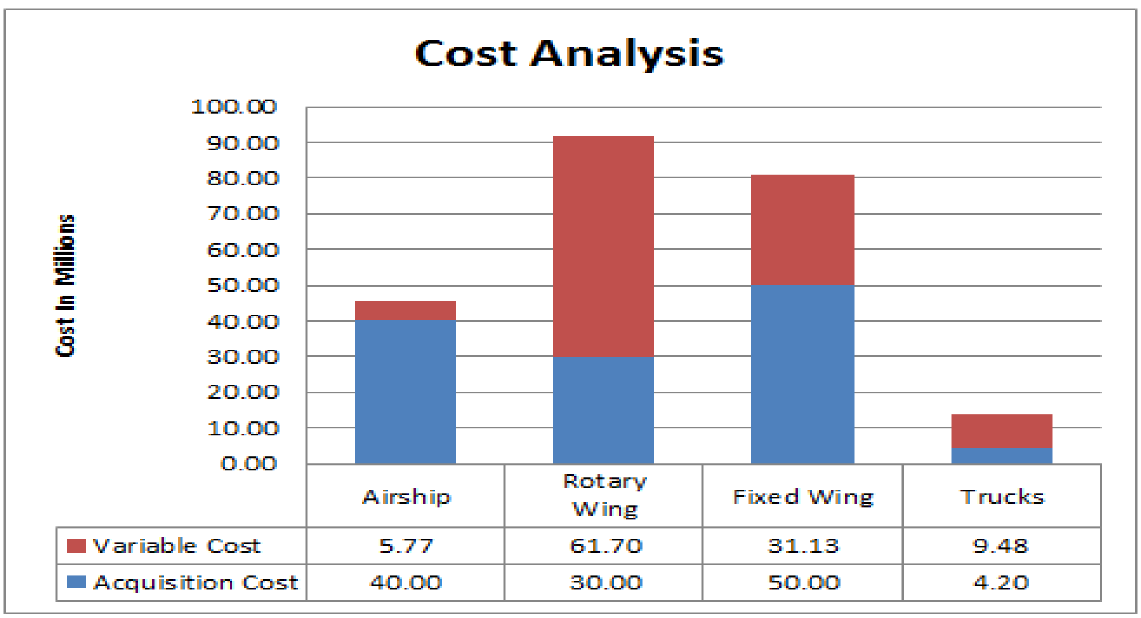


Figure 6.5: Total Cost of Operation for a Year's Operation by Vehicle Type

The cost of operating the trucks is significantly lower than that of the UAVs, despite the long traveling time. Referring to the cost data in table 6.1, the cost of operating the UAVs per hour ranges from $1,200 to $3,000, whereas the average cost of operating truck is only

$100 per hour. Furthermore, the acquisition costs of the trucks are much lower as well. The higher cost of traveling for both rotary wing and fixed wing UAVs makes the cost of operation much more expensive than trucks.

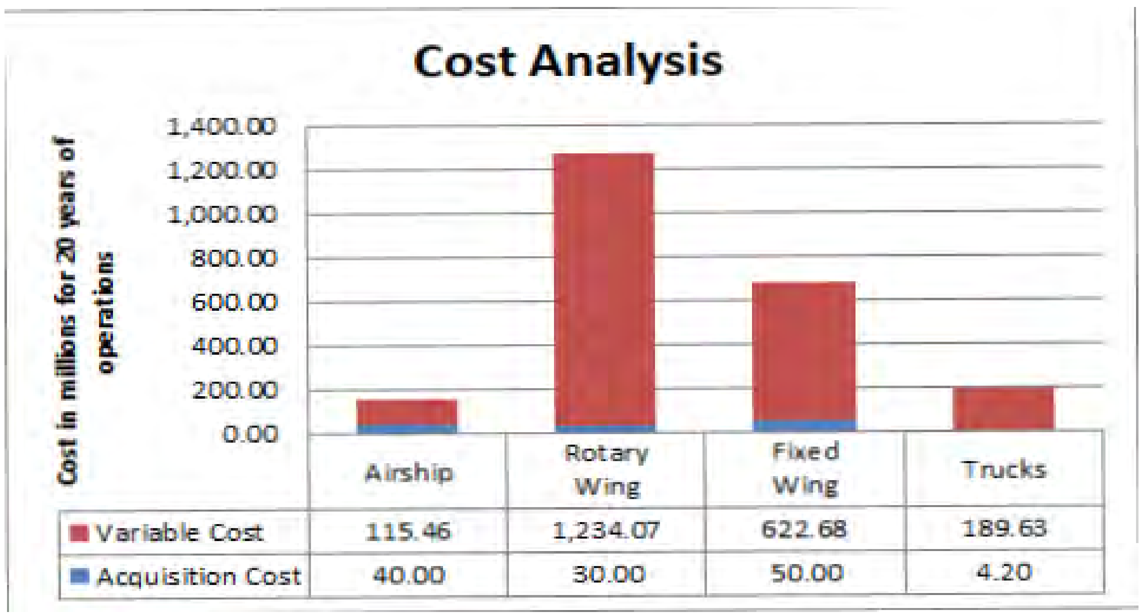


Figure 6.6: Total Cost of Operation for 20 Years of Operation by Vehicle Type

In the long run, the variable cost affects the total cost of operations substantially. For example, considering a 20-year operation, without considering the cost of acquisition, the airship costs about $115 million to operate and the fixed wing UAV up to $622 million, whereas a truck up to $189 million to operate. Figure 6.6 illustrates the total cost of operations for a twenty-year period for each vehicle type. Thus, in the long run, the airship's low variable cost could eventually help to mitigate the high cost of acquisition and prove to be a much more attractive choice than the use of trucks.

6.5 Experiment 3: Sensitivity Analysis of Increasing EAB Stockpile

The supplies stockpiled by each EAB are expected to range between seven days to a month's worth. A sensitivity analysis is conducted to determine the effects of increasing stockpile on the cost of supporting the operations. The scenario setup and the simulation runs are the same as Experiment 1 and 2. In this experiment, the stockpiles are varied between 1, 2, 3 or 4 weeks of supplies stored at each EAB. When stockpiles increase, the request per load increases accordingly. However, the number of days to fulfill the orders remains the same. For example, the logistics center has to deliver four weeks of supplies within three days after request. This places more demand on the logistics center and it is expected that more platforms are required to manage the loads and deliver them to the EABs on time.

In this study, the use of the fixed wing and rotary wing UAVs is not considered because their cost of operations has made them not feasible for use in the long run for large-volume supply of cargo. Based on the results highlighted in the previous experiments, the use of airships and trucks are used to determine the effects of increasing the stockpiles on the cost-effectiveness of the solutions. Sections 6.5.3 and 6.5.2 provides the analysis of the increased number of platforms to support the missions, and the costs of operations when the stockpiles are varied.

6.5.1 Data Generated from Experiment 3

Tables 6.11 and 6.12 show the performances data of airship and trucks when stockpiles are varied. Each table shows the performances of the respective vehicle type and the number of vehicles to support the missions when the stockpiles are varied. The data in the tables shows the mean values and the standard deviation generated from the regression runs. The description of the performance measures are found in Table 6.5.

EAB Stockpile	**7 days**	**14 days**	**21 days**	**28 days**
Required number of airship	1	1	1	1
Avg. No. of Trips per Vehicle	792.11 ± 1.17	579.44 ± 1.14	504.75 ± 1.18	470.25 ± 1.15
Avg. Distance per Trip per Vehicle	456.91 ± 0.23	414.99 ± 0.28	394.76 ± 0.32	382.72 ± 0.33
Avg. Load per Trip per Vehicle	65704.33 ± 89.79	88375.10 ± 75.31	100140.25 ± 64.67	105698.32 ± 55.42
Avg. Travel Time per Vehicle	291.52 ± 0.11	296.23 ± 0.12	299.33 ± 0.13	299.72 ± 0.14
Avg. MaintTime per Vehicle	77.87 ± 0.12	78.00 ± 0.14	77.94 ± 0.15	78.01 ± 0.16
Avg. Unused time per Vehicle	293.81 ± 0.98	531.58 ± 1.70	661.71 ± 2.30	736.13 ± 2.59

Table 6.11: Performances of the Airship when the EAB Stockpiles are Increased from Seven days to 28 Days

Supplies Stockpile	7 days	14 days	21 days	28 days
Required number of trucks	14	17	22	30
Avg. No. of Trips per Vehicle	221.95 ± 0.28	168.58 ± 0.31	123.63 ± 0.25	90.86 ± 0.30
Avg. Distance per Trip per Vehicle	498.94 ± 0.42	447.85 ± 0.33	432.35 ± 0.32	432.98 ± 0.34
Avg. Load per Trip per Vehicle	17650.54 ± 8.51	18805.69 ± 3.90	19268.52 ± 3.45	19609.24 ± 2.69
Avg. Travel Time per Vehicle	1830.82 ± 1.40	1661.68 ± 1.11	1610.48 ± 1.05	1612.92 ± 1.12
Avg. MaintTime per Vehicle	155.97 ± 0.12	156.18 ± 0.13	156.08 ± 0.13	156.13 ± 0.13
Avg. Unused time per Vehicle	388.05 ± 1.78	1321.71 ± 3.94	2510.35 ± 5.12	4167.92 ± 8.88

Table 6.12: Performances of the Trucks when the EAB Stockpiles are Increased from Seven days to 28 Days

6.5.2 Platform Analysis

Referring to Table 6.11, the number of airship remained the same despite the increase in stockpile in the EABs. This is because the airship has a large capacity, which allows it to accommodate more loads per request. However, this large capacity could disadvantage small requests, such as food and parts. From Figure 6.7, it is shown that the airship remains underutilized, despite the increase in load. In certain flights, the airship flew off without filling up until its full capacity, because of priority deliveries or because there is no other shipments in the pipeline. Thus, the airship flew off with small supplies in their cabin. To circumvent this problem, this thesis recommends that a rotary wing or fixed wing UAV be used to transport small supplies, whereas the airship is used for larger shipments.

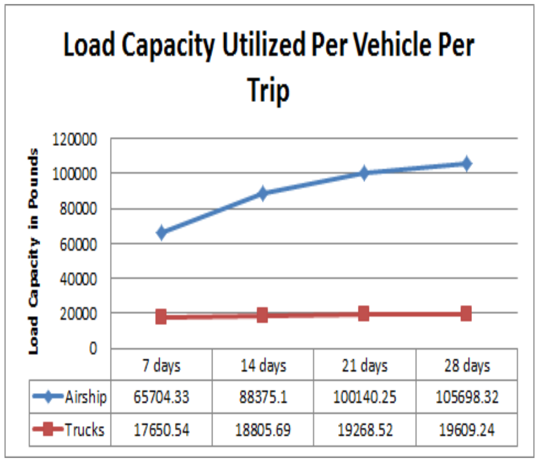
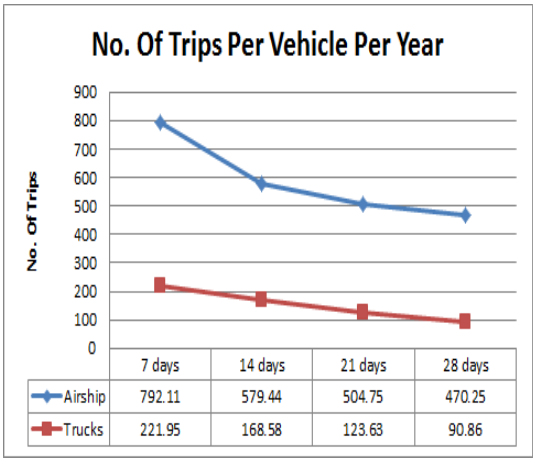


Figure 6.7: Load Capacity Utilized by Each Vehicle for Each Trip. This figure shows the utilization of the vehicle capacity when the EAB stockpile is increased from seven days to 28 days.

One observation is the increase of the number of trucks needed when the stockpiles are increased. While stockpiles are increased, the number of days to fulfill all orders remains the same. This means that the trucks have to deliver more loads within the same three days turnaround period. As the load increases, the capacity of trucks increasingly full up till it is almost full, as seen in Figure 6.7. To compensate for the increasing load, a fully utilized capacity, and the short time to deliver, the number of trucks to deliver is increased. Another observation is the almost exponential increase in the number of trucks in the initial stage, before stabilizing to a linear increase of seven to eight trucks per week increase of stockpile. This is because the capacity of the trucks was not fully utilized at the initial stage but reaches the plateau after 21 days, as seen in Figure 6.8, thus stabilizing the increase in number of trucks to a linear degree.



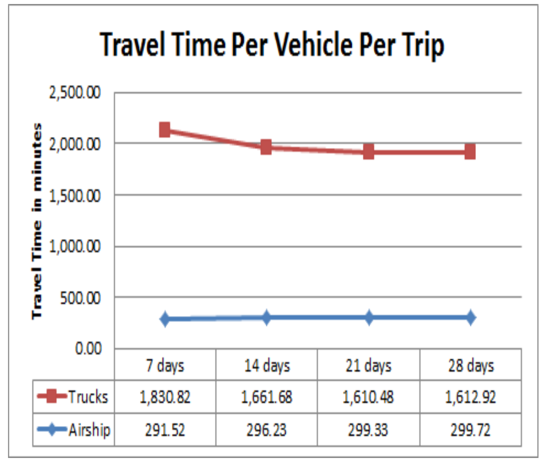
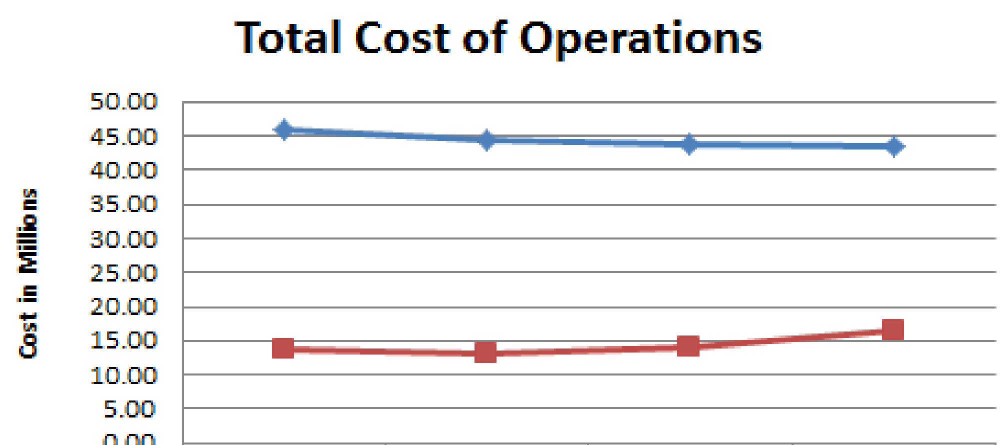


Figure 6.8: Travel Times and Trips Operated by Each Vehicle. This figure shows a decrease in the number of trips for each vehicle when the EAB stockpiles are increased from seven days to 28 days. The amount of time taken by the truck for each trip is decreased as well, whereas amount of time taken for the airship remains constant.

6.5.3 Cost Analysis

Figure 6.9 shows the cost comparison between trucks and airship for the supply of the EABs. The cost of operations does not deviate much with an increase of stockpiles in the EABs. To support the larger volume of goods, the number of trucks has to increase from 14 trucks (for seven-day stockpile) to 30 trucks (for 30-day stockpile).



	7 days	14 days	21 days	28 days
Airship	45.77	44.29	43.77	43.52
Trucks	13.68	13.04	13.90	16.33

Figure 6.9: Total Cost of Operation for a Year as Two Functions of the Supply Storage Capacity at All EABs

6.6 Insights

Based on the studies conducted, UAVs operating as the main transport in the future are shown to be promising. The efficiency of UAVs is much higher than the traditional means of trucks, which leads to less manpower requirements. With DOD's vision of further increasing the efficiency of UAV, by allowing one pilot to operate up to six UAVs, the number of personnel to operate the UAVs will decrease substantially in the future. As the U.S. defense budget is increasingly streamlined, as seen in recent years, the budget cuts have led to the downsizing of the military. Having platforms that are more efficient may help to mitigate the effects of downsizing the forces in the future.

Current technology costs are extremely high now. The cost of an UAV is about 10-20 times more than that of a truck. Given that the fixed wing and rotary wing UAVs have relatively small capacities, it might not be cost-effective to use them to support the high-volume demands of the EABs in the operating theater. It might be better suited for missions requiring fast responses, e.g., forward troops requiring urgent supplies within hours or urgent medical evacuations. Such trips are expected to have smaller load requests but need to be fulfilled within hours.

As the pace of technology advances, the cost of acquiring and operating the UAV is expected be less expensive. This cost reduction is anticipated to be positively impacted when commercial delivery companies, e.g., Amazon, FedEx, etc., enter this area of development. With large-scale adoption of this technology, the cost of research and development will eventually fall and help to mitigate the cost of UAV employment in the logistics missions.

When comparing the performances of the various assets, the airship appears to be the most promising technology, since it excels in all aspects of performance. This result assumes that it meets the performances that the manufacturers have promised, given that airship is a new technology and has not been reliably proven to date. There is increasing use of airship technology for airborne sensors and communication links in Afghanistan and Iraq. They currently operate within short ranges and carry small sensor payloads, as compared to large cargo loads requirements. However, emerging and maturing technologies may soon demonstrate the feasibility of the proposed concept.

The study also shows that to sustain cargo delivery, we would require platforms in the same capacity class as the airship. The current developments of fixed wing and rotary wing UAVs with small capacity are not cost-effective for large-volume cargo delivery. This fact means that more developments and investments must be poured in to develop UAVs with high payload capacity, in the range near the airship's capacity of 132,000 lbs.

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CHAPTER 7:
Conclusion

7.1 Conclusion

This thesis explored the logistical supply operations of the Distributed Air Wing (DAW). One concept proposed by SEA-20B is to disperse the assets of the aircraft carrier to Expeditionary Airbases (EABs), which are land airbases dispersed across the theater of operations to cover the full area of the theater.

This thesis proposes to follow the Marine Aviation Logistics Supply Program II (MALSP II) for the resupply of EABs. Instead of the parent node delivering directly to the Forward Operating Base (FOB), a series of intermediate nodes are setup between the two nodes with the aim of reducing the response time required to supply the FOBs. Furthermore, the program uses a Just-in-Time and Pull-and-Push concept with the aim of reducing the storage spaces required in each base.

This thesis proposes to use Rota Naval Base in Spain and Sembawang Naval Base in Singapore to bridge Vietnam to the Parent supply base via the North Atlantic Route. The Guam Naval Base is used to bridge Philippines to the parent node via the Pacific Route. Furthermore, supply bases are to be set up in the Subic Bay and Cam Ranh Bay to act as main supply bases to the EABs to Philippines and Vietnam respectively.

As the DAW concept aims for operational implementation in the in 2025–2030 time-frame, this thesis proposes to adopt future technologies to replace trucks as the main transportation means for resupply. Nominal models of logistics assets including an airship, fixed wing Vertical Take Off Landing (VTOL) UAV, and fixed wing VTOL are proposed and explored in this thesis.

According to [6], the turnaround time, i.e., the time from requests to the time when the requested cargo is delivered from Main Operating Base (MOB) to the FOB should be within three days. Using this as a guideline, this thesis uses a two-stage approach to propose the fleet size and mix and determining the feasibility of the solutions. Using South China Sea as

the operating theater, the EABs are dispersed to different locations across Vietnam and the Philippines to provide strike and sensor capabilities within the perimeter of the South China Sea. This thesis first uses a Vehicle Routing Problem optimization model to determine the optimal fleet size and mix to support the logistics supply. This recommendation is tested to ensure it meets the criteria of three days turnaround time via the second stage, which uses a discrete event simulation to simulate the logistics supply and record the data for analysis.

Experiments were run to compare the efficiency and cost of operations of the logistics concept. The results and analysis show that the airship is the most promising technology. It offers the highest payload capacity per minute and per mile, and its cost of operations is cheaper than trucks in the long run. Notably, the fixed wing and rotary wing technologies could deliver the requested cargo about five to ten times faster than trucks. The current developments of the fixed wing and rotary wing UAVs that have a small capacity are not cost-effective for large cargo delivery. Thus, as a result, more trips were necessary to fulfill all orders. The increased number of trips coupled with the high cost of technology means that the total cost of operation is about six times more expensive than trucks. Thus, the two UAVs are less attractive options than trucks. Despite the high costs, these UAVs have a high response rate and could deliver the goods faster than the airship and trucks. They could instead be deployed to serve as cargo trucks for forward troops or serve emergency requests, i.e., requests requiring a small amount of supplies in a short time. To summarize, airships are best for sustainment, whereas fixed wing and rotary wing UAVs are best suited for quick response missions.

This thesis also explored the amount of supplies to be stored in each camp as a potential efficiency driver. An EAB is expected to carry about seven to 30 days of supplies each. Even if the EAB carries 30 days of load, the resupply turnaround time criteria remains as three days. The experiment results show that the cost of operations does not differ much regardless of whether the EAB carries seven days or 30 days of supplies. The number of trucks required to support this will be doubled due to the delivery of a large amount of supplies within three days. The fixed wing and rotary wing UAVs were not considered because they were not cost-effective to deliver a large amount of supplies.

In conclusion, this thesis has shown that EAB resupply could be successfully achieved by adopting the MALSP II concept. UAVs provide faster response than trucks but are more

costly due to high technology cost. With the commercial companies gradually entering the UAV market, and a large scale adoption of the technology, the cost of technology is expected to decrease substantially, which could make UAV logistics resupply capabilities a much more attractive option into the future.

7.2 Future Works

Due to scope of this thesis, factors such as the platform's defensive capabilities and the effects of the supply chain were not studied. There are several topics of research arising from this work which should be pursued.

1. The models developed could include more real-world features. More models could be added to the simulation to provide a better representation of the real world. Models that could be included are: (1) communication models to simulate the data links between the ground control station and the UAVs, (2) warehouse models to simulate the full logistics inventory process, (3) adversary models and weather models to simulate the interruptions of the logistics flow, and (4) the DAW combat scenario models to incorporate the actual logistics expenditure.
2. This thesis is closely connected to the capstone project developed by SEA-20B. The capstone project could leverage the simulation models built as an analysis tool to evaluate different EAB locations, cost-effectiveness of the solutions, and determine the total cost of operations of the recommended solutions.
3. The data sources are currently unavailable, since the platforms are under development. Thus, this thesis uses open source data to evaluate the platform performances and gain preliminary insights to the logistics concept. Accurate data could be obtained from the manufacturers in future and added to the model to verify the actual performances of the platform.
4. The entire supply chain consists of upper echelons such as the expeditionary supply bases and the parent base. The upper echelon could trigger a chain effect which could affect the performances of our logistics concept. For example, delays due to inclement weather, delays due to communication problems, or delays due to poor responses of the upper echelons, can delay the delivery efforts from the MOBs to the EABs. Thus, the entire supply chain should be modeled and studied to understand the effects of the supply chain on the logistics supply to the EABs.

5. Cargo vehicles are vulnerable to attacks during movement and they would require additional assets to escort them. The costs of engaging protective escorts could increase the cost of operations. Therefore, a research can be conducted to determine the possible manned or unmanned escorts required to protect the cargo UAVs. Furthermore, researches could be conducted to determine the various air defense weapons that the cargo UAVs could use to protect them, without exceeding the payload limits.
6. Each run of the discrete event simulation takes about one minute to complete. The discrete event simulation models could be used as a decision support tool to perform rapid decision making in the employment of the air assets for resupplying the EABs. A graphics user interface and a platforms database could be implemented for the commanders to modify the model, without changing the source codes, and perform rapid simulations to aid the decision making.

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